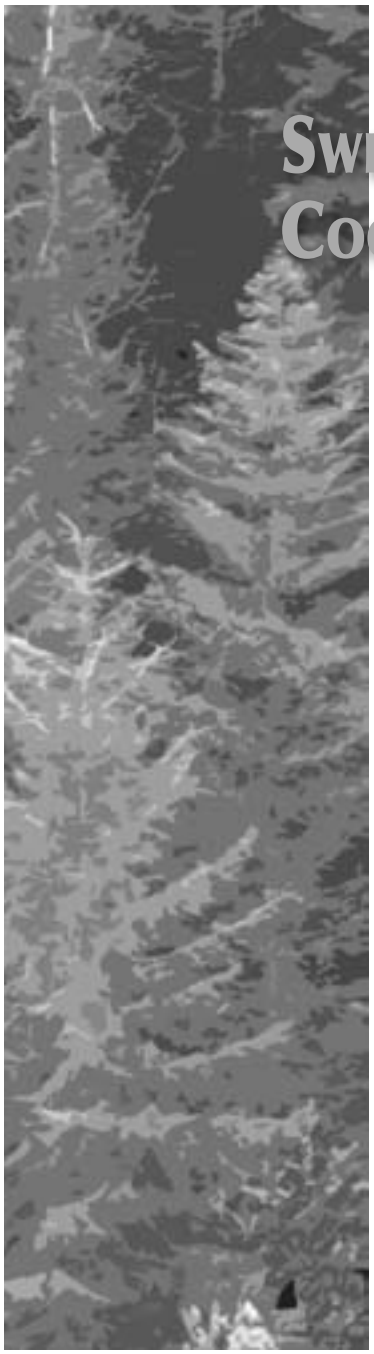
Swiss Needle Cast Cooperative

Annual Report 2004

Oregon State University

SNCC



Swiss Needle Cast Cooperative

2004 Annual Report

Edited by Doug Mainwaring, Acting SNCC Director
Layout by Gretchen Bracher, FCG

SNCC Income Sources and Expenditures 2004

Income	
Membership dues	$107,500
Oregon State Legislature	$120,000
Total Income	$227,500
Expenditures (Projects):	
Salaries and Wages:	$ 98,650
Supplies and Services	$ 79,950
Travel	$ 9,728
Indirect costs	$ 18,178
Total expenditures	***$206,506***
Net total	***$ 20,994***

Contents

To: SNCC Members
From: Doug Mainwaring
Date: September 2004
Subject: 2004 Annual Report

SNCC is now eight years old, and I thank the members for their support this year. Appreciation is also owed to the Oregon State Legislature for their continued financial support of the Coop's efforts. This year's annual report contains summaries on the progress made on our 10 projects, as well as additional reports from related SNC studies.

Acknowledging the accomplishments of the Coop to date, a decision was made last year by the membership to scale down research and member dues. With the recognition that new efforts should be directed more towards practical research, the membership produced a new mission statement and objectives. An obvious and ever-present impediment to new research is the budget: with a final year of funding from the state legislature ($120,000), and the current level of membership dues, the projects adopted for 2005 tie up all but $40,000 of Coop budgets to 2008, much of it going to monitoring.

I regard it a priority in the next year to identify specific end goals that the membership wants to see accomplished. Once established, we can identify those steps necessary to reach those goals. With tighter budgets, a refocus on goals should make our efforts more efficient, and hopefully generate increased enthusiasm.

I would like to thank this year's project investigators for their fine efforts in generating new information concerning Swiss needle cast: Alan Kanaskie, Doug Maguire, Jeff Stone, Dan Manter, and Robin Rose.

I would also like to thank and acknowledge the active members, whose interest and enthusiasm keep this cooperative moving in the right direction: Mark Gourley, Alan Kanaskie, Charlie Moyer, Greg Johnson, Matt Higgins, Jim Carr, Walt Kastner, Margaret Banks, Scott Ketchum, Jerry Anderson, Dennis Creel, and Dean Stuck. In addition, I would like to express appreciation to Tom Adams and Penny Wright for their help in acquainting me with the bureaucratic side of cooperative organizations.

Finally, I would like to recognize longtime Coop Director Greg Filip, who stepped down as director after being hired as the Region 6 Pathologist with the PNW Research Station in Portland. Under his leadership, the Coop has learned a great deal about SNC in a short period of time.

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Highlights

- ✓ An aerial survey was conducted over 3 million acres in western Oregon. A total of 177,000 acres of Douglas-fir had obvious symptoms of Swiss needle cast. In general, symptoms of Swiss needle cast decreased in 2004 compared to 2003.
- ✓ Research continues on 10 different projects in 2004 including: aerial and ground survey, growth impact study, pre-commercial thinning, sulfur application efficacy, fungal genetics, vegetation management and fertilization, GIS-based fungal colonization modeling, and analysis of two silvicultural trials.
- ✓ Randy Johnson, Barb Gartner, Doug Maguire, and Alan Kanaskie published their research in the journal Forest Ecology and Management with the title "Influence of Bravo fungicide applications on wood density and moisture content of Swiss needle cast affected Douglas-fir trees."
- ✓ Zeina El-Hajj, Kathleen Kavanagh, Cathy Rose and Zahi Kanaan-Atallah published their research in the journal New Phytologist with the title "Nitrogen and carbon dynamics of a foliar biotrophic fungal parasite in fertilized Douglas-fir."
- ✓ Rick Kelsey and Dan Manter published their research in the journal Forest Ecology and Management with the title "Effect of Swiss needle cast on Douglas-fir stem ethanol and monoterpene concentrations, oleoresin flow, and host selection by the Douglas-fir beetle."
- ✓ Coop-funded research will be shared with the general public in a one-day conference, to be held in Eugene on November 16, 2004.

Projects for 2005

- ✓ Continue aerial survey to monitor SNC in Oregon.
- ✓ Continue to monitor effect of aerial sulfur applications on SNC infection.
- ✓ Continue to refine GIS-based modeling of fungal colonization and Douglas-fir growth.
- ✓ Analyze Starker potassium/manganese/oil treatments
- ✓ Conduct branch-level foliage retention surveys of Growth impact and PCT plots in acknowledgement of the decreasing confidence field crews have of ground-based foliage retention measurements.

Background and Organization

A major and recent challenge to intensive management of Douglas-fir in Oregon and Washington has been the current Swiss Needle Cast (SNC) epidemic. Efforts to understand the epidemiology, symptoms, and growth losses from SNC have highlighted gaps in our knowledge of basic Douglas-fir physiology, growth, and silviculture. The original mission of the Swiss Needle Cast Cooperative (SNCC), formed in 1997, was broadened in 2004 to include research aiming to ensure that Douglas-fir remains a productive component of the Coast Range forests.

SNCC is located in the Department of Forest Science within the College of Forestry at Oregon State University. The Membership is comprised of private, state, and federal organizations. Membership dues vary depending on forestland ownership. One annual report, project reports, and newsletters are distributed to members each year. All projects are carried out in cooperation with specific members on their land holdings.

Mission Statement

To conduct research on enhancing Douglas-fir productivity and forest health in the presence of Swiss needle cast and other diseases in coastal forests of Oregon and Washington.

Objectives

(1) Understand the epidemiology of Swiss needle cast and the basic biology of the causal fungus, Phaeocryptopus gaeumannii.

(2) Design silvicultural treatments and regimes to maximize Douglas-fir productivity and ameliorate disease problems in the Coast Range of Oregon and Washington.

(3) Understand the growth, structure, and morphology of Douglas-fir trees and stands as a foundation for enhancing productivity and detecting and combating various diseases of Douglas-fir in the Coast Range of Oregon and Washington.

Swiss Needle Cast Aerial Surveys, 1996 to 2004

Alan Kanaskie, Mike McWilliams, Keith Sprengel, Dave Overhulser

Survey procedures

Aerial surveys for SNC have been conducted in April and May each year since 1996. The observation plane flies at 1,500 to 2,000 feet above the terrain, following north-south lines separated by 2 miles. Observers look for areas of Douglas-fir forest with obvious yellow to yellow-brown foliage, a symptom of moderate to severe Swiss needle cast damage. Patches of forest with these symptoms (patches are referred to as polygons) are sketched onto computer touch screens displaying topographic maps or ortho-photos and the position of the aircraft.

The area surveyed extends from the coastline eastward approximately 30 miles (or until symptoms are no longer visible), and from the Columbia River south to Brookings. We survey approximately 2 to 3 million acres each year. We occasionally have surveyed the Cascade Range, but the low damage levels do not justify repeated surveys.

Results and discussion

The Coast Range survey began on May 6 and ended on May 17, 2004, and covered approximately 2.35 million acres of forest. In the 2004 survey we mapped 176,594 acres of Douglas-fir forest with obvious symptoms of Swiss needle cast; 116,342 acres north of the Lincoln-Lane county line, and 60,252 acres south of the Lincoln-Lane county line. The easternmost area with obvious SNC symptoms was approximately 25 miles inland from the coast. Most of the areas with symptoms that can be detected from the air occurred within 18 miles of the coast. Figures 1,2 and 3 show the trend in damage from 1996 through 2004. The survey maps for 1996 through 2004 appear in figures 4-12.

The 2003 and 2004 survey results suggest a trend of decreasing area with symptoms of Swiss needle cast. The 2004 survey did not extend inland quite as far as it had in previous surveys, and it covered 650,000 fewer acres than it did in 2003 (the survey extends inland only as far as observers can detect symptoms). Ground-based observations within the survey area also suggest a very slight improvement in the foliage color and retention in 2003 and 2004. Even though this trend might be encouraging, the survey still shows an impressively large area with significant damage from Swiss needle cast.

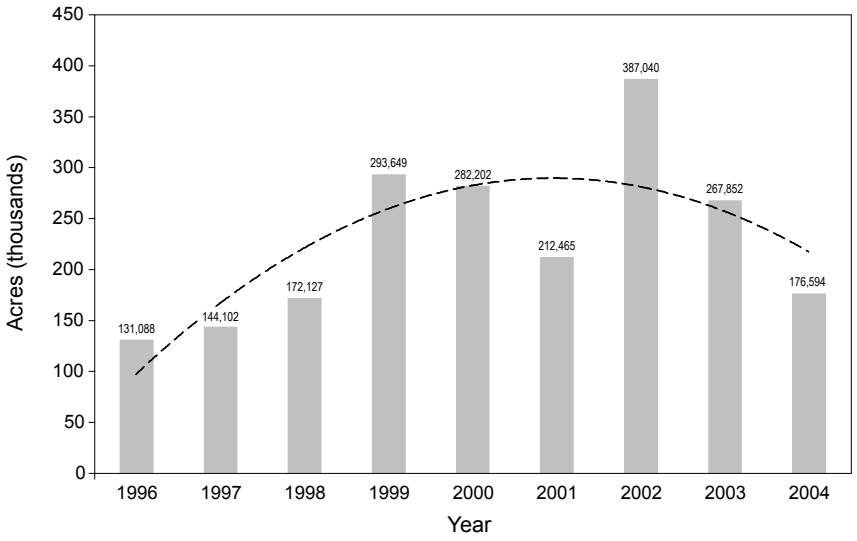

Figure 1. *Trend in area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys in April and May, 1996-2004.*

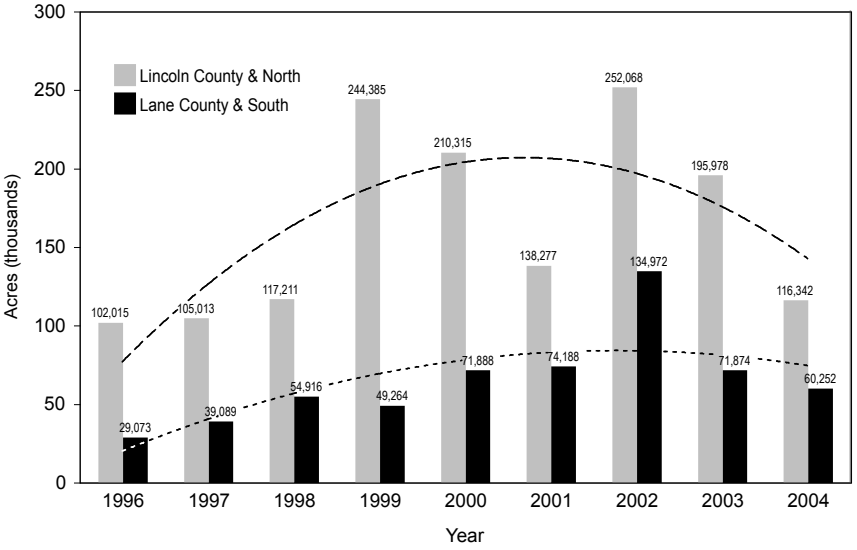

Figure 2. *Area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys in April and May, by zone, 1996-2004.*

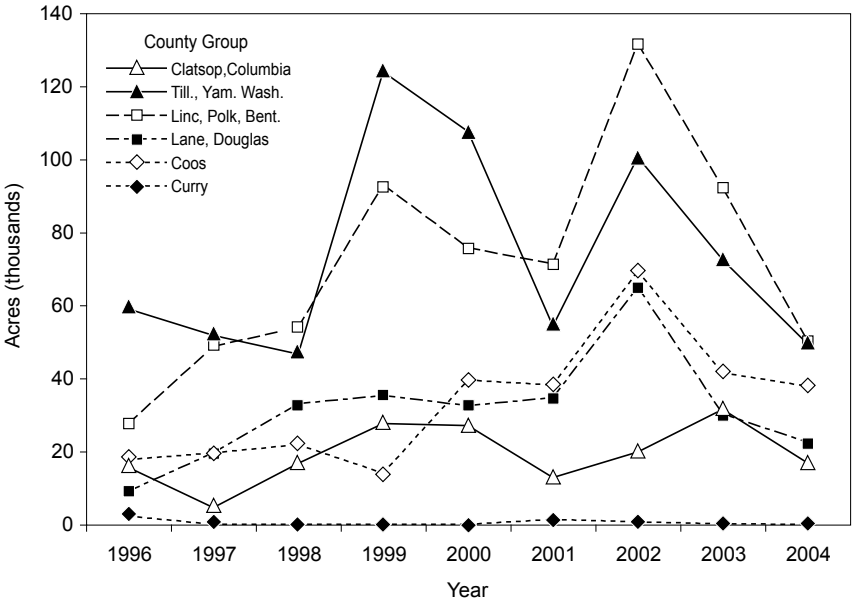

Figure 3. *Area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys in April and May, by county group, 1996-2004.*

We expect some year-to-year variation in the survey due to timing of the flights relative to the development of SNC symptoms. Because symptoms develop rapidly during April and May, later surveys usually detect more areas with symptoms than those conducted earlier. The 2004 survey was flown from May 6 to May 17, which was earlier than the 2003 survey (flown May 19 to May 28, 2003), but at the approximate center of our target survey period.

The 2004 survey was particularly challenging for observers. SNC symptoms were rather late developing, and an early bud-flush confounded observation. Cloudy conditions during the narrow survey window also made observation and mapping unusually difficult. More than in any other year, observers urged caution in interpreting the aerial survey results.

The aerial survey provides a conservative estimate of damage because observers can map only those areas where disease symp-

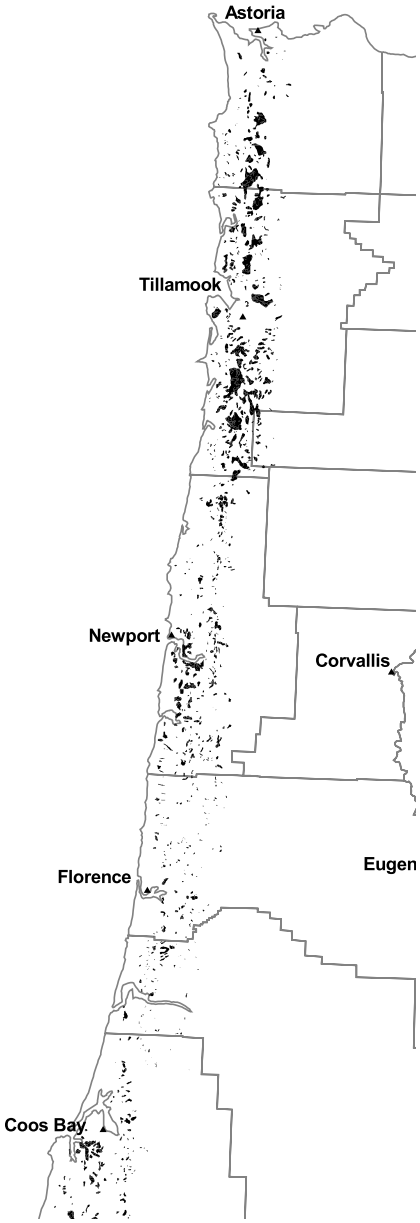

Figure 4. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in April,* **1996**.

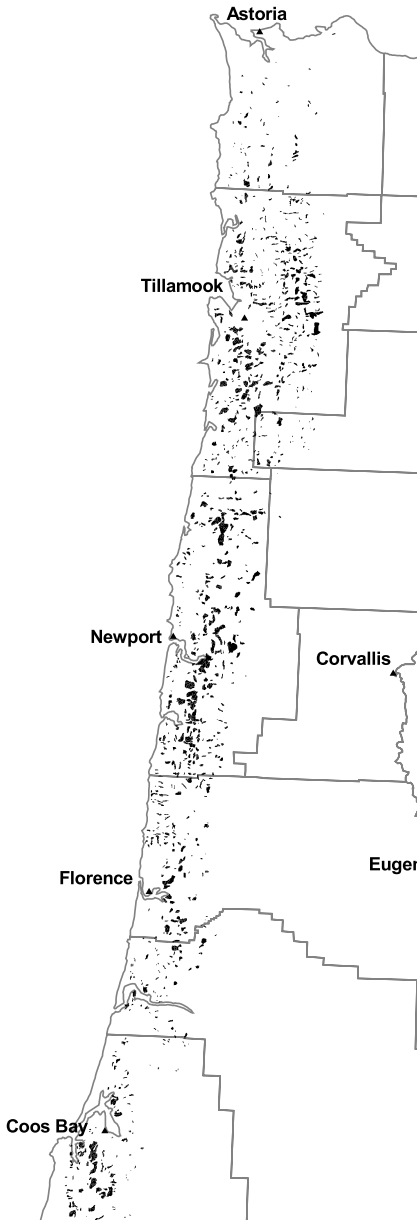

Figure 5. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in April,* **1997**.

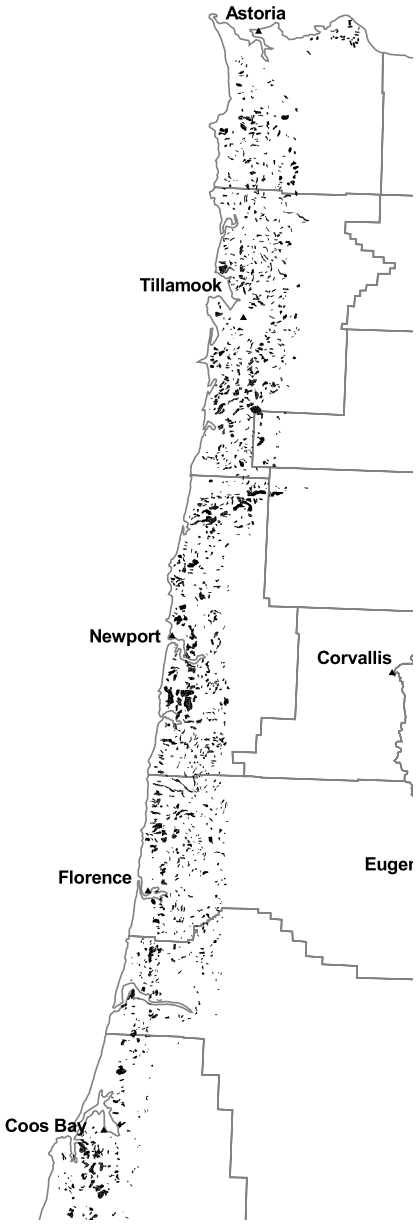

Figure 6. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in April and May,* **1998**.

toms have developed enough to be visible from the air. We know (from permanent plot data and ground checks) that Swiss needle cast occurs throughout the survey area, but discoloration often is not pronounced enough to enable aerial detection. The total amount of forest affected by Swiss needle cast is far greater than indicated by the aerial survey. The aerial survey does, however, provide a reasonable depiction of the extent of moderate to severe damage, coarsely documents trends in damage over time, and establishes a zone in which forest management should take into account the effects of the disease.

Acknowledgments

The survey was conducted by the Oregon Department of Forestry Insect & Disease and Air Operations sections, and was funded by the Oregon State University Swiss Needle Cast Cooperative, the USDA Forest Service Forest Health Monitoring Program, and

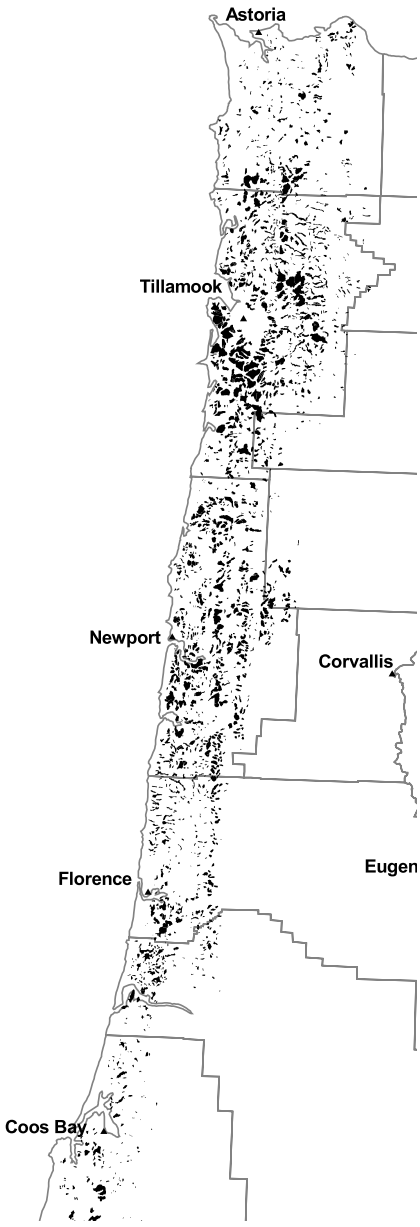

Figure 7. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in April and May* **1999**.

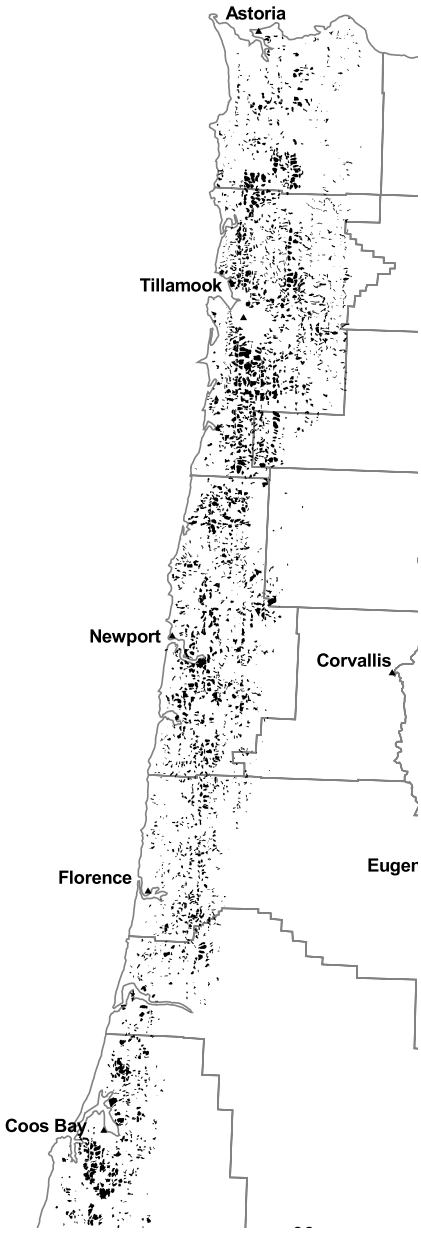

Figure 8. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in April and May,* **2000.**

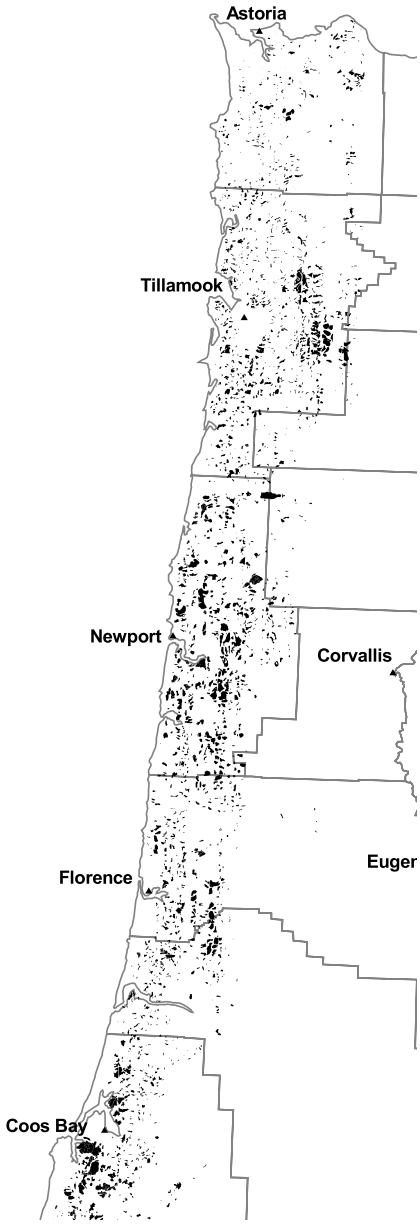

Figure 9. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in April and May,* **2001.**

the Oregon Department of Forestry. Jim Baranek (ODF) piloted the plane. Mike McWilliams (ODF), Keith Sprengel (USFS), and Dave Overhulser (ODF) were the aerial observers.

Note:

The GIS data and a pdf file for the SNC survey can be accessed via the ODF web page at:
http://www.odf.state.or.us/fa/FH/maps.htm

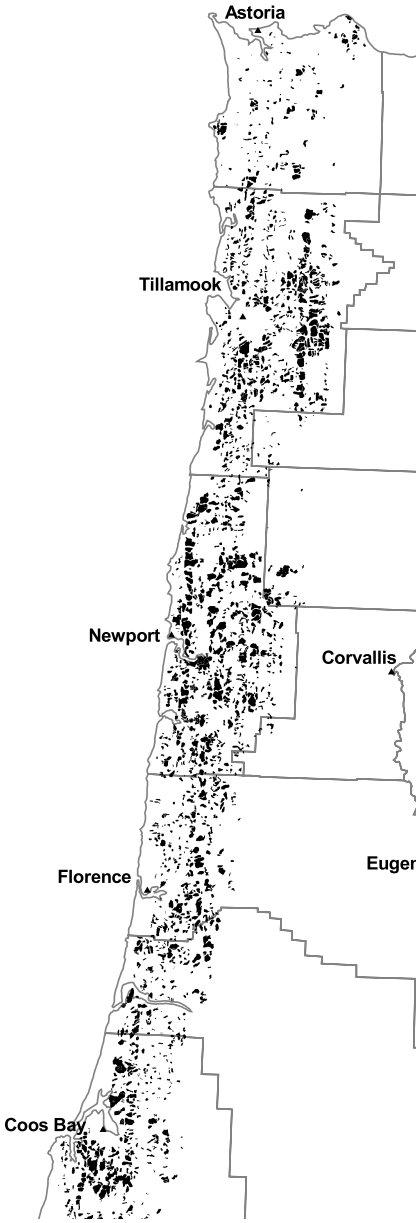

Figure 10. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in May,* **2002**.

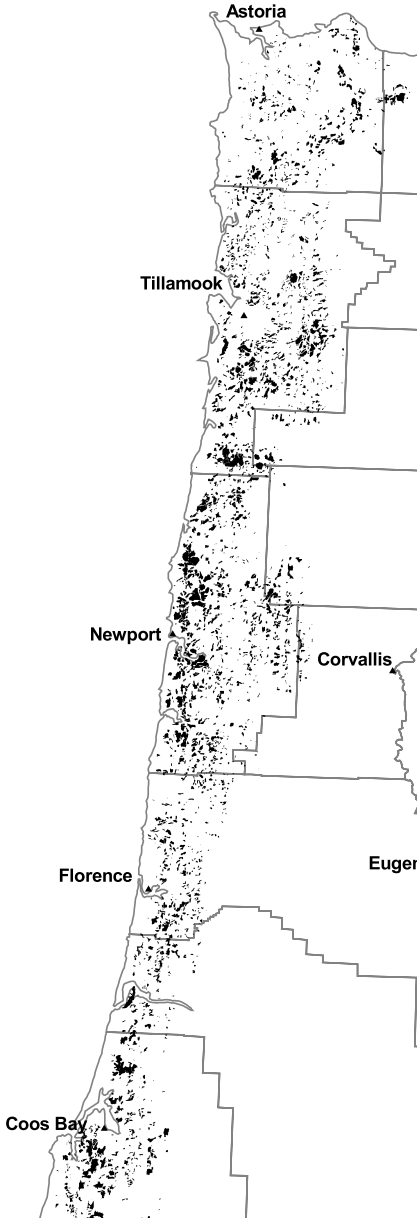

Figure 11. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in May,* **2003**.

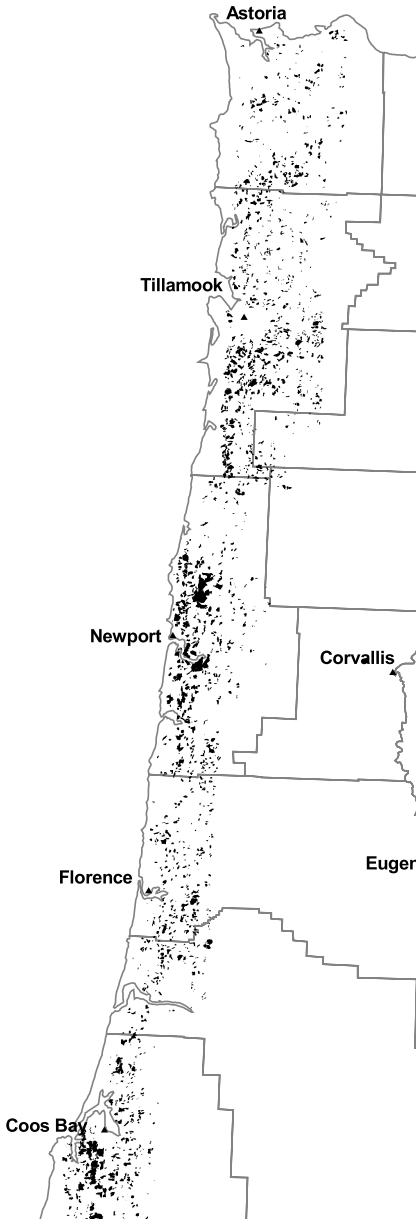

Figure 12. *Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during an aerial survey in May,* **2004**.

Trends in Damage from Swiss Needle Cast in Permanent Plots in 10- to 30-year-old Douglas-fir Plantations

Alan Kanaskie, ODF; Doug Maguire, OSU

Background

The Permanent plot network was established in 1997 to provide a basis for monitoring Swiss needle cast (SNC) damage and for quantifying impacts of SNC on tree growth. This paper describes the results of monitoring various indicators of SNC damage. Growth impacts are discussed in a separate paper.

Objectives

The objectives of the study are: 1) to describe trends in the severity of damage from Swiss needle cast in randomly chosen 10- to 30-year-old Douglas-fir plantations in the Coast Range of western Oregon; 2) to estimate the area (acres) affected by SNC, and; 3) to ground-truth areas mapped by aerial survey.

Methods

In 1997, 77 Douglas-fir plantations in the northern Coast Range of Oregon were randomly chosen for monitoring trends in damage from Swiss needle cast. The target population was all Douglas-fir plantations between 10 and 30 years total age (1996 age) located within 18 miles of the coast, north of Newport and south of Astoria. With much cooperation from landowners, a list of plantations meeting these criteria was assembled. Plantations were selected from this list with probability proportional to size (area). The target population included 4,504 plantations covering 187,545 acres. The initial sample included 77 plantations covering 6,873 acres (figure 1). One plantation was lost from the study in 1999 due to cutting.

Swiss needle cast damage was assessed in April and May of each year since 1997. The 1997 assessments were based on a sample of ten trees per stand (two trees at each of five points along a transect). Beginning in 1998, assessments were made on ten trees per stand located in the 1/5-acre permanent growth monitoring plots (Phase III) located at point 5 of the 1997 transects. The same ten trees in each plot were assessed

each year beginning in 1998 unless mortality or breakage necessitated substitution.

Stand Ratings

Stand ratings were designed to provide a quick method of estimating Swiss needle cast severity by assessing average stand condition during a brief walk-through of the stand. All ratings refer to the Douglas-fir component of the stand in the vicinity of the permanent plots. Overall stand discoloration was rated on a scale of 1 to 4 for as follows: 1 = normal green color, with Douglas-fir similar in color to healthy hemlock; 2 = slight yellowing; 3 = moderate yellowing, and; 4 = severe yellowing and/or browning.

The Swiss needle cast severity rating for the stand was described according to the following 6-class system (needle retention was assessed on unshaded secondary laterals in the upper middle crown, usually near whorl 5 to 7 from the tree top):

1 = *Healthy, normal-appearing Douglas-fir stand*. Typical of the east-slope Coast Range stands that are dark green, growing normally, and with normal needle retention (3.5 years or more mid-crown). Douglas-fir and hemlock of the same size do not differ appreciably in color. Swiss needle cast may be present, but causing symptoms only on 3 year-old and older needles.

2 = *Almost normal, but showing slight yellowing*. Needle retention normal (3.5 or more years present on most trees) Douglas-fir will appear slightly more yellow than hemlock or spruce. Crown still appears full and dense. No reduction in height growth increment.

3 = *Yellowing obvious*. Most trees retaining 2.5 to 3 years of needles. No obvious height increment reduction.

4 = *Yellowing obvious*. Most trees retaining 1.5 to 2 years of needles. Reduction in height growth increment by 25% of normal for one or more of the last three years will not be obvious, but may occur on a few trees.

5 = *Very yellow stand*. Most trees retaining 1 to 1.5 years of needles. Height growth increment is reduced by at least 25 percent of normal for one or more of the last 3 years on at least 50% of trees, but not as much as described in "6" below.

6 = *Stand is extremely yellow to yellow-brown, with very sparse foliage*. Most trees retaining 1 year of needles or less in upper crown. Obvious height growth reduction for 4 or more years. These are the most severely damaged stands, typical of the Juno Hill, Beaver, and Hebo areas.

Individual Tree Assessments on Plots

Ten co-dominant or dominant trees in each 1/5-acre permanent plot were assessed for damage from Swiss needle cast. Sample trees were permanently tagged so the same trees could be assessed each year.

Needle Retention was estimated for the middle of each third of the live crown (upper, middle, lower) by examining secondary lateral branches and estimating the average number of annual needle compliments present (a *secondary lateral* is a branch that originates on the side of the main lateral branch). Sample branches were chosen to represent the average condition in the part of the crown being examined. The number of annual needle compliments present for each third of the live crown was estimated to the nearest 0.1 year as follows:

0.5 = 50 % of one-year-old needles (1998) remain, all older needles gone

1.0 = All one-year-old needles remain, older needles gone

1.2 = One-year-old needles plus 20 % of two-year-old needles remain

1.6 = One-year-old needles plus 60 % of two-year-old needles remain

2.0 = One- and two-year-old needles remain, older needles gone

2.5 = One- and two-year-old needles remain, plus 50% three year old needles remain

3.0 = All one-, two-, and three-year-old needles remain....

...and so on up to 6.0.

Whorl-5 needle retention was estimated by examining branches in the fifth whorl down (occasionally the sixth or seventh whorl) from the top of the tree. Needle retention, i.e., percentage of the full compliment of needles remaining on the branch at the time of the assessment, was estimated for each of the four most recent internodes of shoot growth on secondary laterals according to

the following "0 to 9" scale:

0 = 0 to 10 percent of full compliment present;

1 = 11 to 20 percent of full compliment present;

2 = 21 to 30 percent of full compliment present;…..

9 = 90 to 100 percent of full compliment present.

Crown indicators

From 1998 to 2000 inclusive, observers estimated the following four indicators, based in part on the US Forest Service Forest Health Monitoring protocols: 1) *crown color* - discoloration of the upper 1/2 to 1/3 of crown, near whorls 5 to 7 from the top, using the 1 to 4 scale previously described for stand color; 2) *crown density* - percentage of sunlight being blocked by all parts of the crown, in 5% classes; *3) foliage transparency* - percentage of sunlight being transmitted through the foliage, in 5% classes; 4) *crown dieback* - percentage of the total crown area that has branch dieback, in 5% classes. For the 2001 and subsequent assessments, crown density and transparency variables were dropped because they had not proven useful in previous analyses.

Results and Discussion

The mean SNC stand rating (1 to 6 scale) increased gradually by nearly one rating class between 1997 and 2004 (figure 2). This trend suggests a general increase in SNC damage over the period based on subjective overview ratings. Although the SNC rating for 2004 was not significantly different from the 2001-2003 ratings, the ratings for the most recent four years were significantly greater than in the first four years.

In contrast, the mean stand discoloration rating did not differ consistently during the same period, but suggested a trend of slightly improving (greener) stand color between 1997 and 2001, then a worsening (more yellow) during the 2002-2004 period (figure 3). One explanation for the discrepancy between these two stand ratings is that the SNC rating incorporates needle retention, height growth increment, and color into the rating. A stand that is very yellow but with good needle retention could lead to different relative ratings on each scale. The stand color rating was originally conceived as a link to aerial survey and remote sensing applications. In practice, the stand discoloration rating has proven very difficult to determine with consistency because of the influence of sunlight, cloud cover, and observer subjectivity.

The SNC rating (1-6) is the preferred method for overview rating of stands because it incorporates many indicators of Swiss needle cast damage. This rating system,

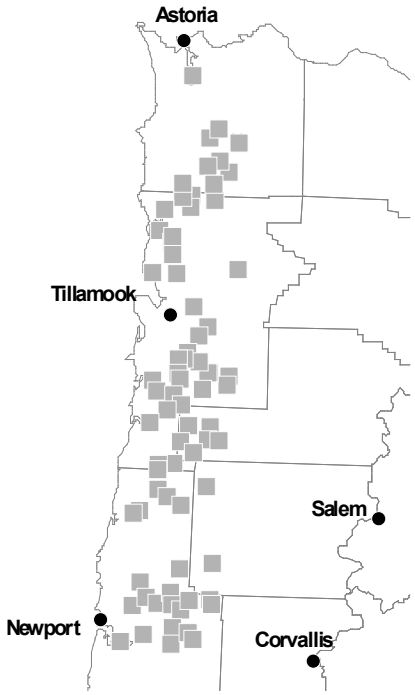

Figure 1. *Location of 76 permanent plots for monitoring Swiss needle cast and tree growth in 10- to 30-year-old Douglas-fir plantations, Coast Range, Oregon.*

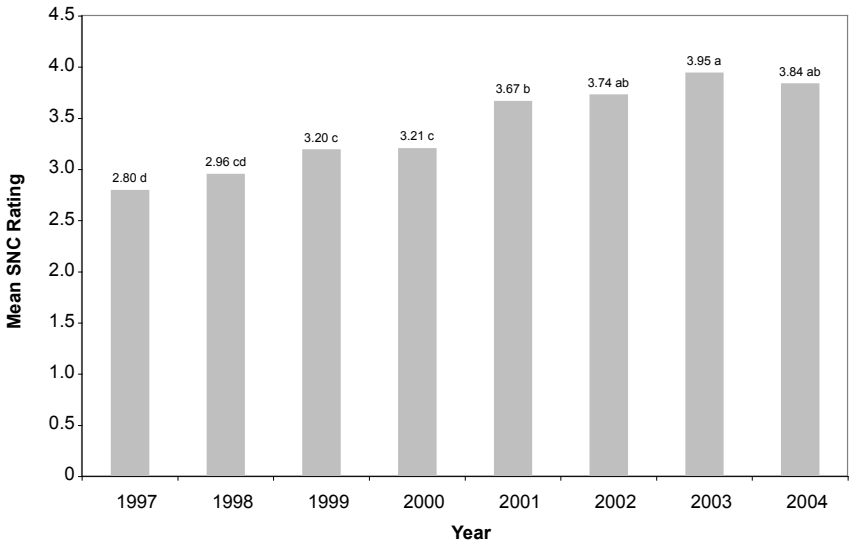

Figure 2. *Mean SNC Stand Rating for 76 permanent plots in 10- to 30-year old (1996 age) Douglas-fir plantations. Swiss needle cast severity rating ranges from 1 (no damage) to 6 (most severe damage). Means with same letter within a data series are not significantly different (analysis of variance, Fisher's LSD, α=.05).*

however, often is not consistent with foliage retention ratings, largely because the SNC rating tends to focus on the condition of the upper crown, which is the only part visible from outside of the stand. The SNC rating is useful as a quick method for determining relative damage for a large number of stands, but should not be used as a substitute for measuring foliage retention or growth reductions from a sample of trees in the stand.

Mean foliage retention (whole crown) for all plots has changed very little between 1998 and 2004. Although some differences among years were significant (Analysis of variance, .05 significance level), they were very small (figure 4).

Analysis by crown thirds consistently has shown that mean foliage retention is lowest in the upper third of the tree crown and greatest in the lower third of the tree crown. Mean foliage retention in the upper and middle crown differed very little from 1998 to 2004 (Figure 5). The decrease in upper third foliage retention from 1998 to 1999 probably reflects the interaction of Swiss needle cast with the high frequency of severe windstorms and a period of very cold weather that occurred during the winter of 1998-1999. The slight improvement in lower-third needle retention in recent years could be due to recent relatively mild winters, as well as increasing tree size and subsequent crown sheltering, both of which could reduce foliage loss.

Mean foliage retention for each permanent plot in 1998 and 2004 appears in figure 6. Mean foliage retention (whole crown) differed significantly (analysis of variance,

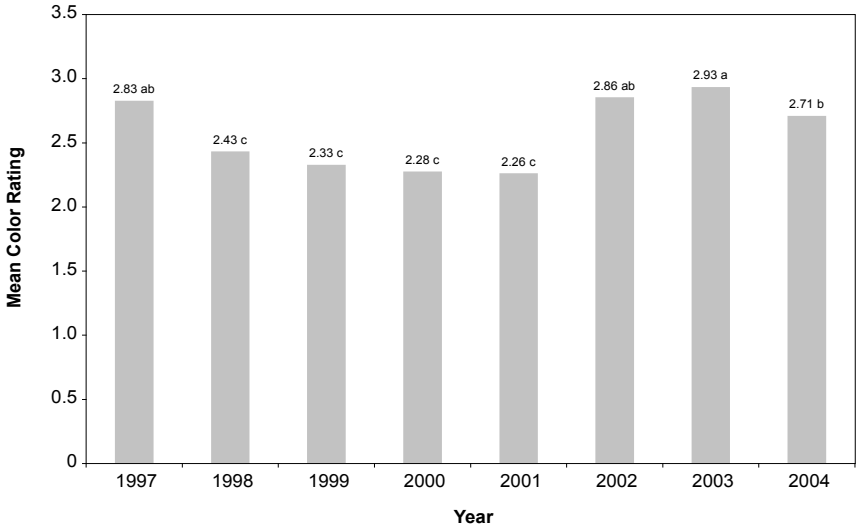

Figure 3. *Mean SNC Stand Discoloration Rating for 76 permanent plots in 10- to 30-year old (1996 age) Douglas-fir plantations. Discoloration rating ranges from 1 (dark green) to 6 (extremely yellow). Means with same letter within a data series are not significantly different (analysis of variance, Fisher's LSD, α=.05).*

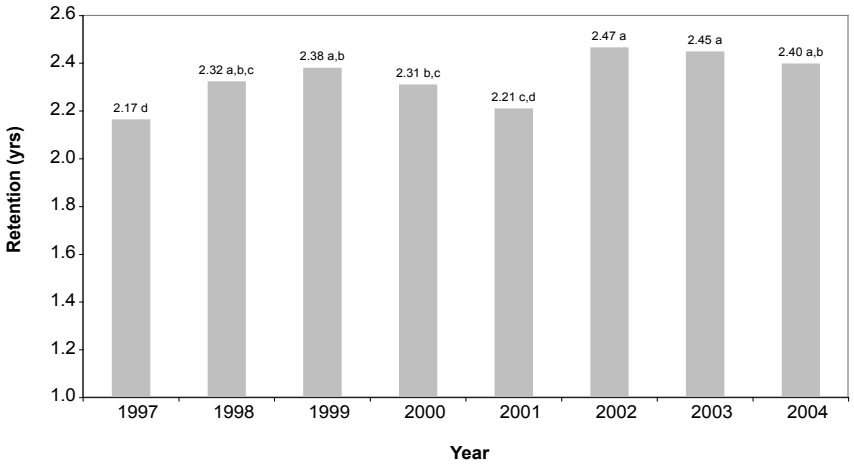

Figure 4. *Mean foliage retention (entire crown) for 76 permanent plots in 10- to 30-year old (1996 age) Douglas-fir plantations. Means with same letter are not significantly different (analysis of variance, Fisher's LSD, α=.05).*

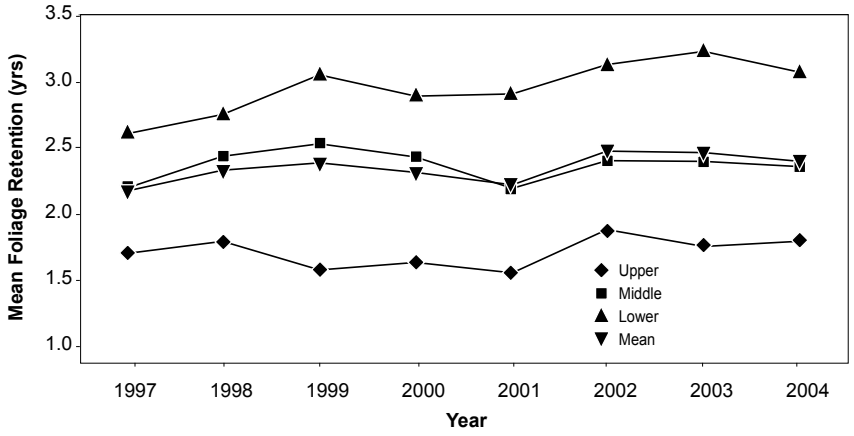

Figure 5. *Mean foliage retention for 76 permanent plots in 10- to 30-year-old (1996 age) Douglas-fir plantations, by crown thirds.*

paired t-tests, α=.05) between 1998 and 2004 on 22 (29 percent) of the plots. During this period, mean needle retention increased on 16 of the plots, and decreased on 6 of the plots (figure 7). We chose 1998 as the reference year rather than 1997 because the 1997 data was from transect trees, while all subsequent data were from permanent plot trees, with the same trees being measured each year. The largest improvement in needle retention for an individual stand during this period was 1.0 annual needle compliments; the largest decrease in retention was 0.77 annual needle compliments. We did not observe any geographic pattern to the changes in needle retention.

Mean needle retention ratings were expanded to estimate the number of acres in each needle retention class for the 187,545-acre population. Since 1997, there has been a general increase in the estimated number of acres with needle retention of greater than 2 annual compliments, and a general decrease in estimated acres with 2 or fewer annual compliments (figure 8).

Conclusions

Based primarily on needle retention ratings, these results show a slight decrease in the severity of damage from Swiss needle cast since 1997. This slight improvement in stand condition and the lack of a consistent trend of worsening damage is encouraging, but the overall poor needle retention in the sample population suggests a continuing severe growth reduction from Swiss needle cast.

Acknowledgements

Thanks to many cooperating landowners and the following individuals for assisting with field work: Jon Laine, Nathan Hunter, John Beeson, Rick Christian, and Michael McWilliams.

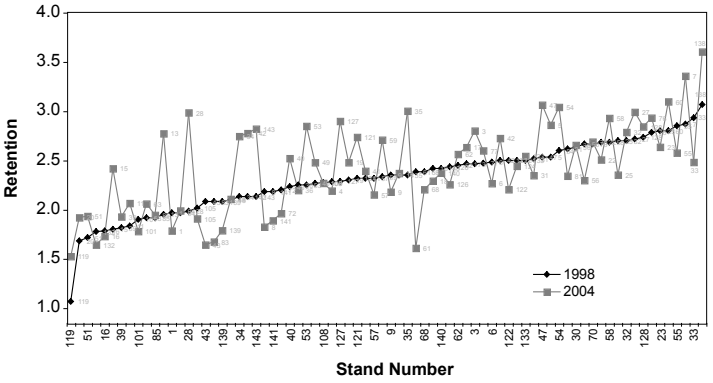

Figure 6. Mean foliage retention (whole crown) in May 1998 and May 2004 for each of the 76 permanent plots in 10- to 30-year-old (1996 age) Douglas-fir plantations, ordered buy 1998 foliage retention.

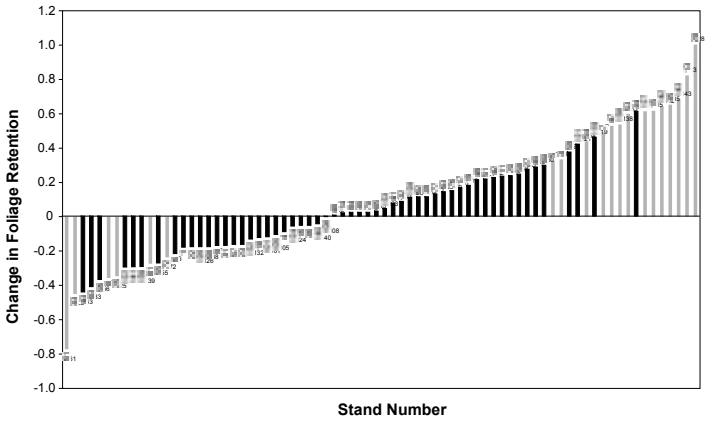

Figure 7. *Increase or decrease in mean foliage retention between 1998 and 2004 in 76 permanent monitoring plots in 10- to 30-year-old (1996 age) Douglas-fir plantations. Grey bars indicate a significant increase or decrease (analysis of variance, Fisher's LSD α=. 05).*

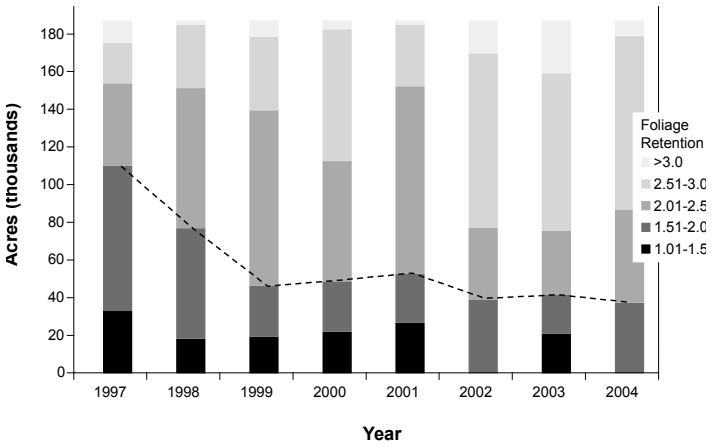

Figure 8. *Distribution of Douglas-fir plantation acreage by needle retention class from 1997 to 2004 for the 187,545-acre population from which sample plantations were chosen. The area below the broken line represent the number of acres with foliage retention of two years or less.*

Trends in Swiss Needle Cast Damage in Thinned and Un-thinnned Douglas-fir Plantations with Varying Intensity of Swiss Needle Cast in the Coast range of Oregon

Alan Kanaskie, Oregon Department of Forestry; and Doug Maguire, Department of Forest Resources, Oregon State University

Background

Many young Douglas-fir plantations in coastal Oregon exhibit extreme symptoms of Swiss needle cast, and these symptoms are associated with reduction in tree growth. Observations suggest that thinning stands with severe Swiss needle cast may increase foliage loss and discoloration, and exacerbate thinning shock. Other observations indicate that early thinning to maintain deep crowns may mitigate some of the growth loss attributed to Swiss needle cast. The response of stands to pre-commercial thinning is expected to vary according to the initial severity of Swiss needle cast at time of thinning.

Objectives

The objectives of the study are: 1) to monitor Swiss needle cast symptoms on permanent plots and the effect of the disease on the growth of individual trees; 2) to measure changes in severity of damage from SNC and associated tree growth responses over time, and; 3) to measure differences in disease severity and tree growth between thinned and un-thinned plots. This reports focuses on trends in the various indices of disease severity between 1998 and 2004. Tree growth responses to pre-commercial thinning and Swiss needle cast appear in a separate report.

Methods

In April and May of 1998, twenty-three paired 0.2 acre square plots were installed in 10- to 16-year-old Douglas-fir plantations (1997 age) in northwest Oregon. Plot locations were selected across a range of Swiss needle cast severity classes and distributed across different topographic aspects (figure 1). One plot in each pair was precommercially thinned to approximately 200 trees per acre in May 1998 (because of initial stocking levels, at two sites the target residual was 100 trees per acre). At five of the 23 locations,

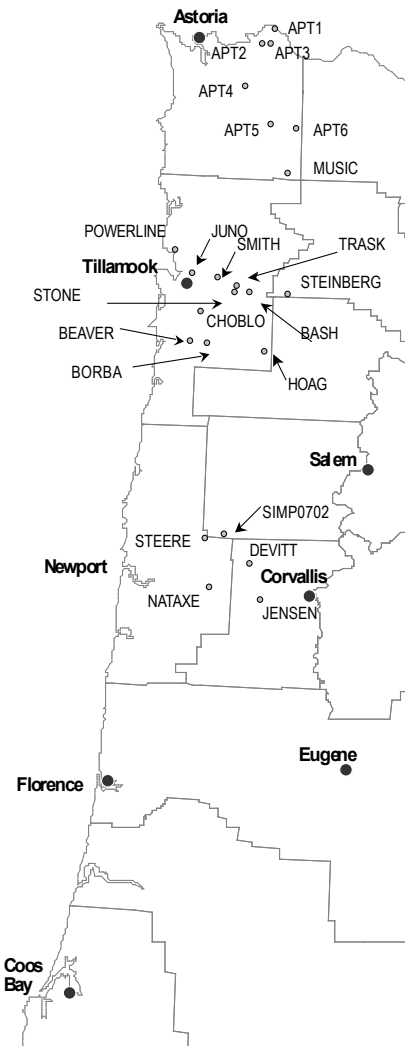

Figure 1. *Location of 23 permanent plot sets to monitor disease symptoms and evaluate growth response to pre-commercial thinning in Douglas-fir plantations with varying intensity of Swiss needle cast in the Coast range of Oregon.*

an additional plot was thinned to approximately 100 trees per acre. During thinning, tree spacing was given priority over tree quality. All crop trees were measured for dbh, total height, and height to crown. Swiss needle cast severity (needle retention and discoloration) was assessed annually during April and May each year since plot establishment. Growth measurements are taken every two years.

Stand Ratings

Stand ratings were designed to provide a quick method of estimating Swiss needle cast severity by assessing average stand condition during a brief walk-through of the stand. All ratings refer to the Douglas-fir component of the stand in the vicinity of the permanent plots. Overall stand discoloration was rated on a scale of 1 to 4 for as follows: 1 = normal green color, with Douglas-fir similar in color to healthy hemlock; 2 = slight yellowing; 3 = moderate yellowing, and; 4 = severe yellowing and/or browning.

The Swiss needle cast severity rating for the stand was described according to the following 6-class system (needle retention was assessed on un-shaded secondary laterals in the upper middle crown, usually near whorl 5 to 7 from the tree top):

1 = *Healthy, normal-appearing Douglas-fir stand*. Typical of the east-slope Coast Range stands that are dark green, growing normally, and with normal needle retention (3.5 years or more mid-crown). Douglas-fir and hemlock of the same size do not differ appreciably in color. Swiss needle cast may be present, but causing symptoms only on 3 year-old and older needles.

2= *Almost normal, but showing slight yellowing*. Needle retention normal (3.5 or more years present on most trees) Douglas-fir will appear slightly more yellow than hemlock or spruce. Crown still appears full and dense. No reduction in height growth increment.

3= *Yellowing obvious*. Most trees retaining 2.5 to 3 years of needles. No obvious height increment reduction.

4= *Yellowing obvious*. Most trees retaining 1.5 to 2 years of needles. Reduction in height growth increment by 25% of normal for one or more of the last three years will not be obvious, but may occur on a few trees.

5 = *Very yellow stand*. Most trees retaining 1 to 1.5 years of needles. Height growth increment is reduced by at least 25 percent of normal for one or more of the last 3 years on at least 50% of trees, but not as much as described in "6" below.

6= *Stand is extremely yellow to yellow-brown, with very sparse foliage*. Most trees retaining 1 year of needles or less in upper crown. Obvious height growth reduction for 4 or more years. These are the most severely damaged stands, typical of the Juno Hill, Beaver, and Hebo areas.

Individual tree Assessments on plots

Ten co-dominant or dominant trees in each 1/5-acre permanent plot were assessed for damage from Swiss needle cast. Sample trees were permanently tagged so the same trees could be assessed each year.

Needle Retention was estimated for the middle of each third of the live crown (upper, middle, lower) by examining secondary lateral branches and estimating the

average number of annual needle compliments present (a s*econdary lateral* is a branch that originates on the side of the main lateral branch). Sample branches were chosen to represent the average condition in the part of the crown being examined. The number of annual needle compliments present for each third of the live crown was estimated to the nearest 0.1 year as follows:

0.5 =50 % of one-year-old needles (1998) remain, all older needles gone

1.0 = All one-year-old needles remain, older needles gone

1.2 = One-year-old needles plus 20 % of two-year-old needles remain

1.6 = One-year-old needles plus 60 % of two-year-old needles remain

2.0 **=** One- and two-year-old needles remain, older needles gone

2.5 = One- and two-year-old needles remain, plus 50% three year old needles remain

3.0 = All one-, two-, and three-year-old needles remain....

...and so on up to 6.0.

Whorl-5 needle retention was estimated by examining branches in the fifth whorl down (occasionally the sixth or seventh whorl) from the top of the tree. Needle retention, i.e., percentage of the full compliment of needles remaining on the branch at the time of the assessment, was estimated for each of the four most recent internodes of shoot growth on secondary laterals according to the following "0 to 9" scale:

0 = 0 to 10 percent of full compliment present;

1 = 11 to 20 percent of full compliment present;

2 = 21 to 30 percent of full compliment present;.....

9 = 90 to 100 percent of full compliment present.

Crown indicators

From 1998 to 2000 inclusive, observers estimated the following four indicators, based in part on the US Forest Service Forest Health Monitoring protocols: 1) *crown color* **-** discoloration of the upper 1/2 to 1/3 of crown, near whorls 5 to 7 from the top, using the 1 to 4 scale previously described for stand color; 2) *crown density* - percentage of sunlight being blocked by all parts of the crown, in 5% classes; *3) foliage transparency* **-** percentage of sunlight being transmitted through the foliage, in 5% classes; 4) *crown dieback* **-** percentage of the total crown area that has branch dieback, in 5% classes. For the 2001 and subsequent assessments, crown density and transparency variables were dropped because they had not proven useful in previous analyses.

Results and Discussion

There was no significant difference in stand Swiss Needle Cast severity or discoloration ratings among years or between thinning treatments. A trend of improving stand condition in the thinned plots is suggested by the increasing difference in stand ratings between thinned and un-thinned plots in 2002 and 2003 (figure 2).

Six growing seasons after thinning, mean needle retention did not differ significantly between thinned and unthinned plots (analysis of variance, Fisher's LSD, α=05). Mean needle retention also did not differ significantly among the six annual measurement periods for any of the treat-

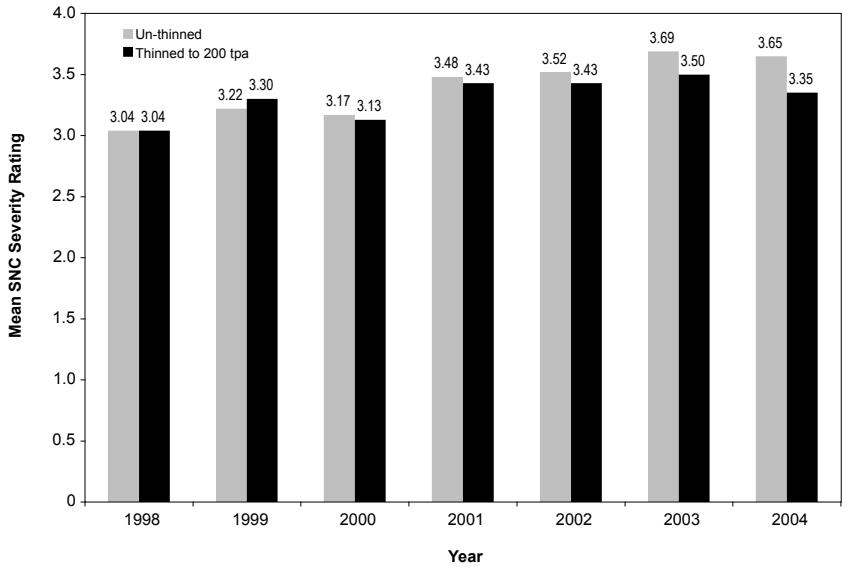

Figure 2. *Swiss Needle Cast Stand Severity Rating for paired thinned and unthinned plots in Douglas-fir plantations affected by Swiss needle cast in the Coast Range of northwest Oregon, 1998 to 2003. Plots were thinned in May 1998. The SNC severity rating did not differ significantly (analysis of variance, α=.05) between thinned and unthinned plots, or among years.*

ments (analysis of variance, .05 significance level) (figure 3). A trend of greater foliage retention in thinned plots compared to un-thinned plots appeared since 2002. This trend was most evident in the lower and middle thirds of the crown (figures 4,5,6,and 7).

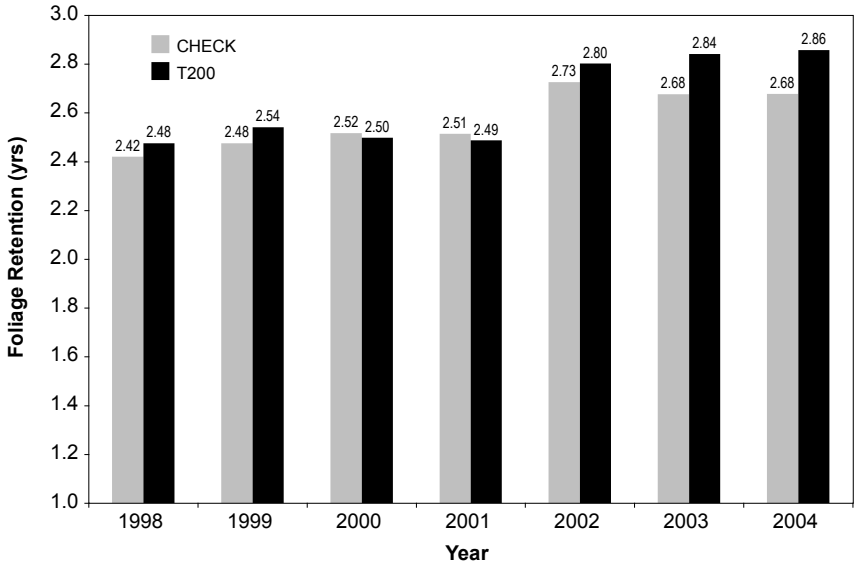

Figure 3. *Mean needle retention (whole-crown) in paired thinned and unthinned plots in Douglas-fir plantations affected by Swiss needle cast in the Coast Range of northwest Oregon, 1998 to 2003. Plots were thinned in May 1998. Mean needle retention did not differ significantly (analysis of variance, α=.05) between thinned and unthinned plots, or among years.*

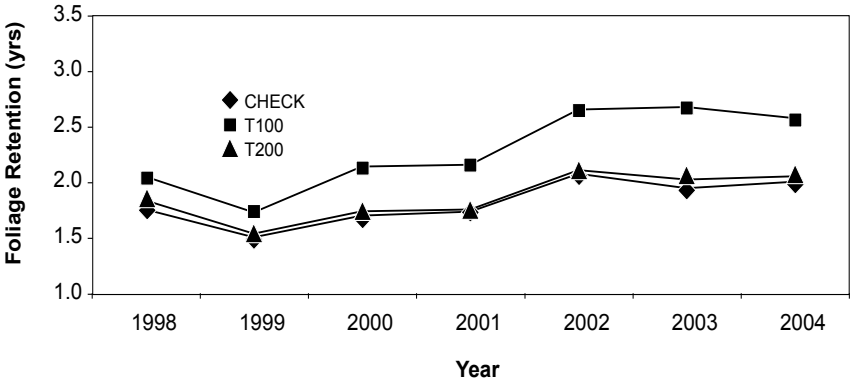

Figure 4. *Mean needle retention from 1998 to 2004 in upper third of crown in thinned and un-thinnned plots. Plots were thinned in May 1998.*

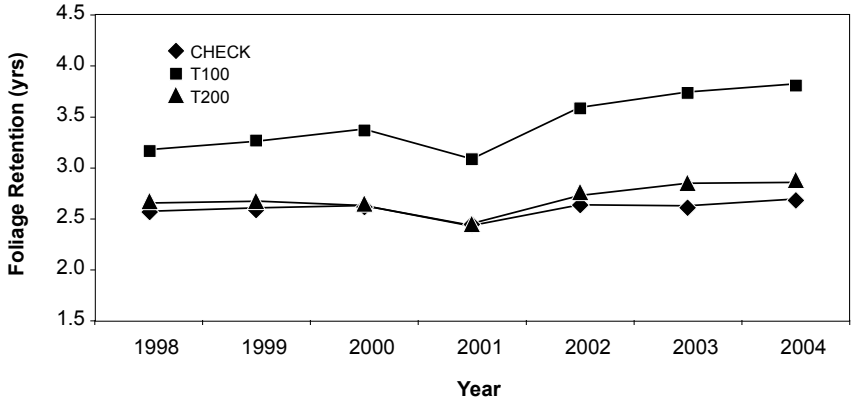

Figure 5 *Mean needle retention from 1998 to 2004 in middle third of crown in thinned and un-thinnned plots. Plots were thinned in May 1998.*

Analysis of data from each installation separately revealed that mean needle retention in 2004 differed significantly between thinned and unthinned plots at 7 of the 23 sites (at the 3-treatment sites, the 200 tpa plots were used for this analysis). At six of these sites (APT4, APT5,APT6, Devitt, Simpson0702, and Steinberg), trees in the thinned plots had greater needle retention than trees in the unthinned plots. At the other site (Powerline - Tillamook County), mean needle retention of trees in the unthinned plot was greater than needle retention trees in the thinned plot (analysis of variance, .05 significance level)(figures 8 and 9).

Five of the sites received two levels of thinning; 100(T100) and 200 (T200) residual trees per acre. A comparison of mean mid-crown needle retention among treatments at these sites six growing seasons after thinning showed significant differences among thinning treatments at three of the five sites (figure 10). At two sites, APT5 and APT6, mean needle retention was greater in the thinned plots than the unthinned plots, but did not differ between the T100 and T200 treatments. At the other site (Devitt), mean needle retention in the T200 plot was significantly greater than in the T100 plot and the unthinned plot.

Some observers have suggested that Douglas-fir plantations with severe Swiss needle cast and poor needle retention will experience more needle loss following precommercial thinning than unthinned plantations. Analysis of the six stands with the lowest needle retention at the time of thinning and the six stands with

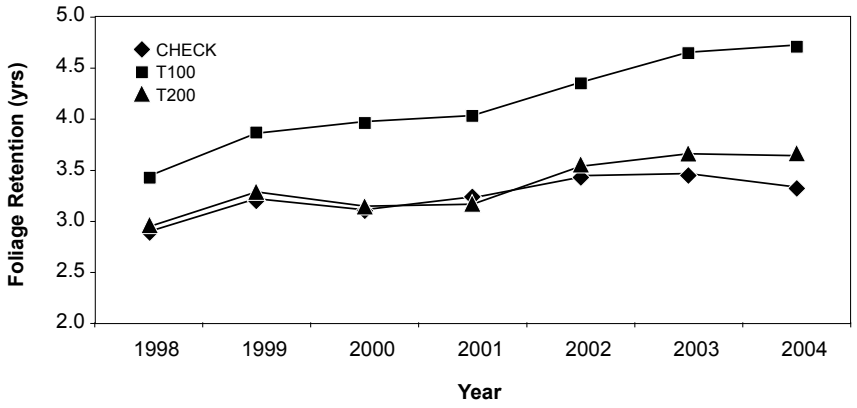

Figure 6. *Mean needle retention from 1998 to 2004 in lower third of crown in thinned and un-thinnned plots. Plots were thinned in May 1998.*

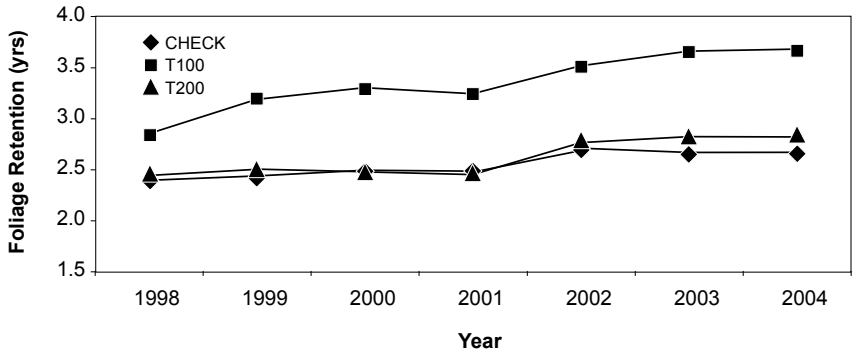

Figure 7. *Mean needle retention from 1998 to 2004 averaged across all crown thirds in thinned and un-thinnned plots. Plots were thinned in May 1998.*

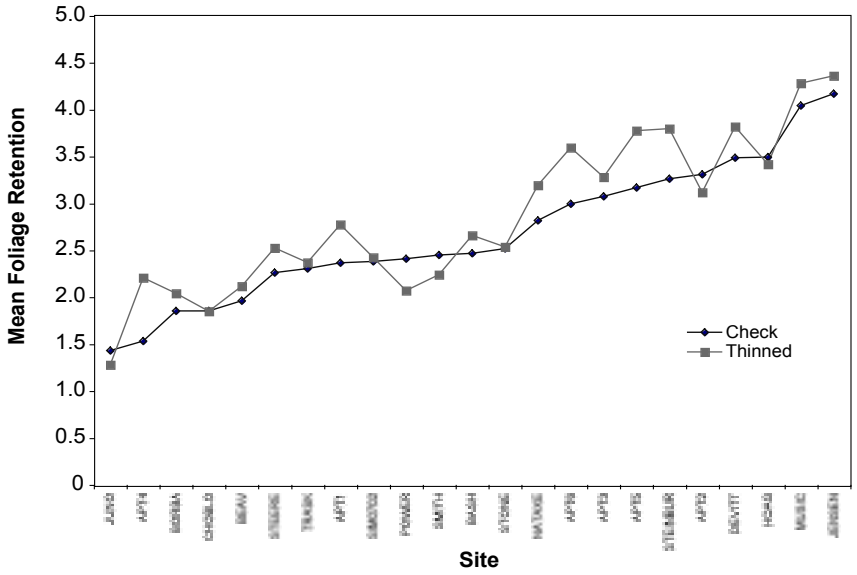

Figure 8. *Mean difference in needle retention in 2004 (six years after thinning) for 23 paired thinned and un-thinned plots of Douglas-fir affected by Swiss needle cast in the Coast Range of northwest Oregon. Plots ordered by needle retention in the un-thinned plot.*

the greatest needle retention at the time of thinning showed little difference in the effects of thinning on needle retention six growing seasons after thinning. Needle retention was significantly lower in the thinned plot at only one of the six sites with the poorest initial needle retention (Figure 11), and at none of the six sites with the highest initial needle retention (Figure 12).

Needle retention is not the only measure of the effects of thinning on tree damaged by Swiss needle cast. A small amount of tree fall, top breakage, and branch dieback occurred at low levels in a few of the thinned plots, but not in the unthinned plots, and especially in plantations with the most severe Swiss needle cast.

A trend is developing for improved needle retention in thinned plots. The expected high loss of foliage following precommercial thinning of stands damaged by Swiss needle cast has not occurred six growing seasons after thinning. Even sites with severe disease (such as Juno Hill and Beaver) showed little difference in mean needle retention between thinned and unthinned plots. Needle retention ratings, although correlated with tree volume growth, likely do not capture the entire the impact of the Swiss needle cast on tree growth. Retention ratings do not account for shoot length, needle size and quality, crown length, or the absolute amount of foliage present, all of which vary considerably in stands affected by Swiss needle cast. A differential tree growth response to thinning across a range of Swiss needle cast damage still is quite possible,

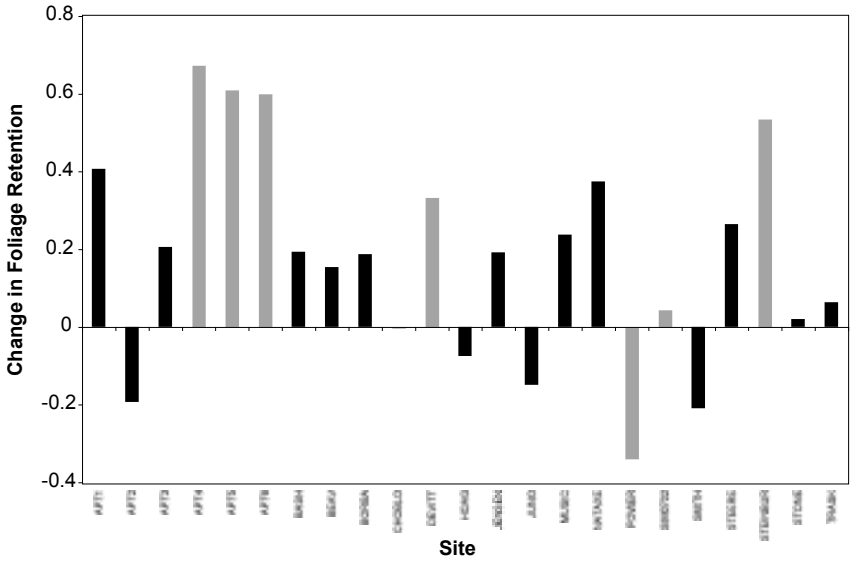

Figure 9. *Mean difference in mid-crown needle retention in 2004 for 23 paired thinned and unthinned plots of Douglas-fir affected by Swiss needle cast in the Coast Range of northwest Oregon. Plots were thinned in May 1998. A bar that extends below the zero line indicates that needle retention in the thinned plot was less than in the unthinned plot; if above the line, needle retention in the thinned plot was greater than in the unthinned plot. Plots with significant differences are indicated by a grey bar (t-test, α=.05).*

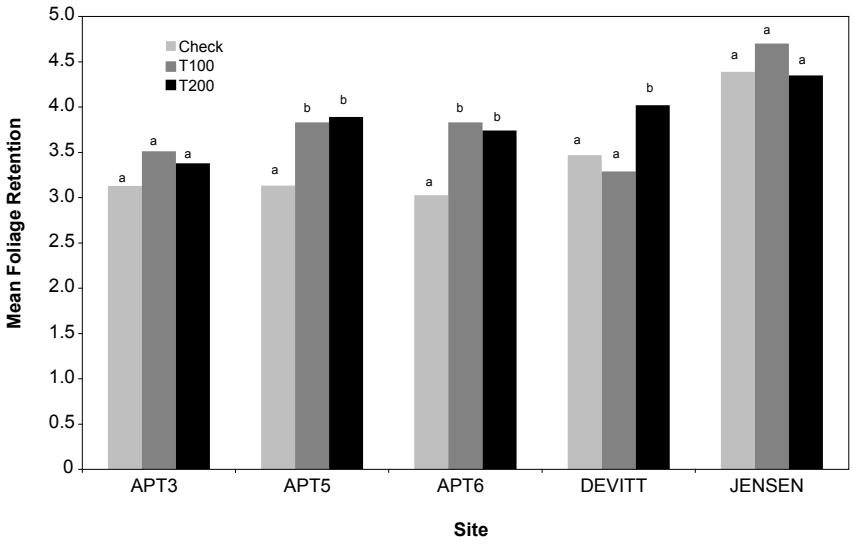

Figure 10. *Mean needle retention (middle crown third) in 2004 (six years after thinning) for sites with three treatments (not thinned; T100 = 100 trees per acre after thinning; T200 = 200 trees per acre after thinning). Means within a site with the same letter are not significantly different (Analysis of variance, Fisher's LSD, α= .05).*

despite the inconclusive needle retention results.

The stands in this study were approximately 12 to 16 years old at the time of thinning. Trees of this age typically have deep crowns and are growing vigorously. Older overstocked stands with relatively low crown ratios could respond quite differently to thinning than the stands in this study.

Conclusions

These results suggest that precommercial thinning does not have an obvious detrimental effect on Douglas-fir plantations affected by Swiss needle cast in the Coast range of Oregon. In fact, the data through 2004 suggest a slight improvement in needle retention in the thinned plots. We conclude that pre-commercial thinning remains a viable stand management tool in the Coast range in all but the most severely damaged stands.

Acknowledgements

The field crew included Jon Laine, Nathan Hunter, John Beeson, and Rick Christian. Plot setup and installation was completed and coordinated by Steve Skinner (ODF Astoria), Matt Howard (ODF Astoria), Steve Dutton (ODF Tillamook), Jim Hines (ODF Tillamook), Dale Anders (ODF Forest Grove), Mike Totey (ODF Philomath), Tom O'Connor (ODF Philomath), Scott Malvitch (ODF Salem), Bryan Capitano (ODF Salem), Chet Smith (ODF Salem), Michael West (ODF Salem), Mark Gourley (Starker Forests), John Washburn (Simpson Timber), Rick Allen (Miller Timber Services), Ted

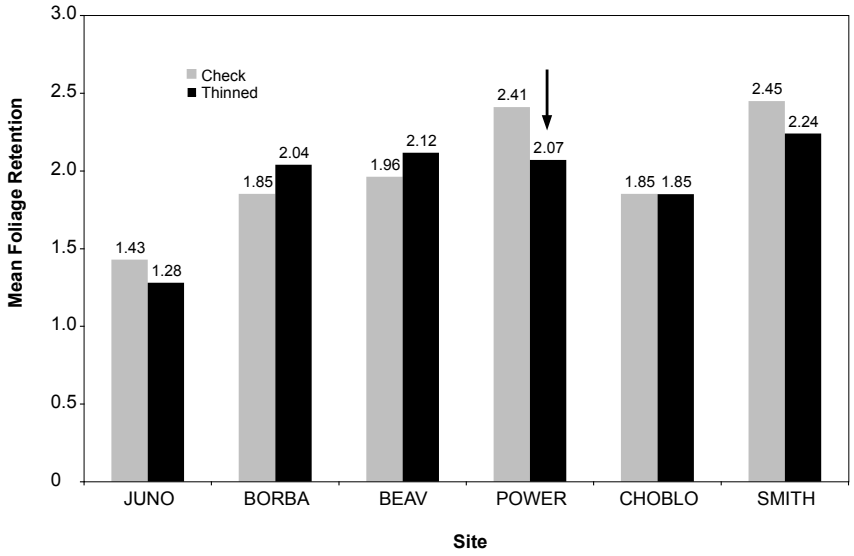

Figure 11. *Mean needle retention (mid-crown) in 2004 (six years after thinning) for paired thinned and unthinned plots with the lowest initial (1998) needle retention. An arrow indicates sites with a significant difference in mean needle retention between thinned and unthinned plots (t-test, α=05).*

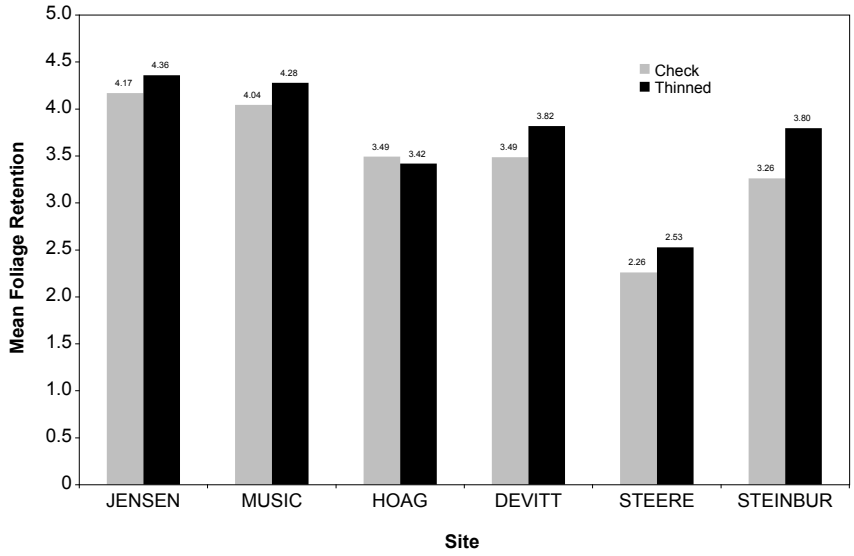

Figure 12. *Mean needle retention (mid-crown) in 2004 (six years after thinning) for paired thinned and unthinned plots with the greatest initial (1998) needle retention. An arrow indicates the sites with a significant difference in mean needle retention between thinned and unthinned plots (t-test, α=05).*

Reiss (Miller Timber Services), Mark Montpas (Miller Timber Services).

Growth Impact Study: Growth Trends Turing the Third 2-yr Period Following Establishment of Permanent Plots

Doug Maguire, OSU, Alan Kanaskie, ODF, and
Doug Mainwaring, OSU

Abstract

Permanent plots in the Growth Impact Study have been remeasured for a third 2-yr growth period. Needle retention was measured on an annual basis from 1997 through 2004, allowing the ratings from 2002 to serve as the initial condition for the 2002-2003 growing seasons. Cubic volume growth of plots with severe Swiss needle cast (SNC) was compared to volume growth of plots with the highest foliage retention (3.9 years), suggesting relative growth losses up to 30% for 2002-2003 (minimum foliage retention of 1.6 years), and average loss of 14% (mean retention of 2.5 years). Although SNC symptom severity had previously fluctuated between 1997 and 2002, the difference in relative growth rate between sites with the highest and lowest foliage retention remained consistent for that 4-yr period. In contrast, growth losses appeared considerably lower for the 2002-2003 growing seasons. Cumulative effects on apparent site index may be lowering expectations, but this effect cannot be strong because site index continues to be a very weak variable in the regression analyses.

Introduction

The Growth Impact Study (GIS) was initiated in 1997 to address two major objectives: 1) to monitor Swiss needle cast (SNC) symptoms and tree growth in 10-30-yr-old Douglas-fir plantations in north coastal Oregon; and 2) to provide an improved estimate of growth losses associated with a given initial level of SNC. Retrospective work conducted in the spring of 1997 established growth losses across a range in SNC severity (Maguire et al. 1998, 2002). Volume growth losses were estimated to average 23% for the target population in 1996, with losses reaching almost 50% in the most severely impacted stands. Total losses in 1996 alone were therefore about 40 MMBF, given that the target population covers approximately 187,000 ac. Permanent plots established in the spring of 1998 and remeasured in 2000 and 2002 confirmed these growth losses. Although SNC symptoms fluctuated from 1997 through 2001, the relationship between needle retention and relative growth losses remained surprisingly stable. The most recent remeasurement was completed in the spring of 2004. The objectives

of this report were: 1) to quantify the most recent 2-yr growth responses relative to initial (2002) SNC severity; and 2) to compare these 2-yr growth responses to those estimated retrospectively for 1996 and on permanent plots for 1998-99 and 2000-2001.

Methods

In the late winter/early spring of 1998, a network of 76 permanent plots was established at locations previously sampled in Phases I and II (retrospective phase) of the Growth Impact Study. The plots were square and 0.08-ha (1/5-ac) in area (31.8 x 31.8 m). Each plot was centered on the 5th point of the ODF transect established in Spring 1997 (Phase I plots were centered on the 3rd point). On each measurement plot, all trees were tagged at breast height and measured for dbh (nearest 0.1 cm). A subsample of at least 40 Douglas-fir was measured for total height and height to crown base (nearest 0.1 m). After 2, 4 and 6 growing seasons, all trees were remeasured for dbh, and all trees from the original height subsample were remeasured for total height and height to lowest live branch. Trees on each plot were also scored for SNC at time of plot establishment in 1998 and just prior to bud break each year from 1999 through 2002. Ten dominant or codominant trees per plot were rated for SNC by dividing the crown vertically into thirds, and estimating the average number of years of foliage retention in each third by visual examination (nearest 0.1 year). Plot ratings were computed as the average of crown thirds from all ten trees.

Statistical Analysis

In growth analyses of the first through third 2-yr periods, all variation in initial needle retention (1998, 2000, and 2002) was assumed totally controlled by SNC. Individual tree values were averaged for the 10 sample trees on each plot to arrive at a plot average ($FOLRET_{98}$, $FOLRET_{00}$, and $FOLRET_{02}$). A simple growth model was fitted to the data from the 74 GIS plots remaining after 2004, using initial foliage retention as the index of SNC severity:

$$\ln[PAI] = b_0 + b_1X_1 + b_2X_2 + \ldots + b_kX_j + b_{k+1}FOLRET \qquad [1]$$

where PAI=plot-level periodic annual increment for cubic volume of Douglas-fir, X_i=plot-level predictor variables, FOLRET is $FOLRET_{98}$, $FOLRET_{00}$, or $FOLRET_{04}$.

Results and Discussion

For the most recent growth period (2002-2003), approximately 90% of the variation in cubic volume PAI was explained by the following model:

$$\ln[PAI] = -0.61477 + 0.80809 \ln(BA_{DF}) - 0.01413\ comba + 0.36315 \ln(FOLRET_{00}) - 0.02422\ (bhage) + 0.28684 \ln(SI) \qquad [2]$$

where PAI = plot-level periodic annual cubic volume growth of Douglas-fir for 2002-2003(m^3/ha)

BA_{DF} = initial Douglas-fir basal area (m^2ha^{-1} in 2002)

comba = initial plot basal area of all species except Douglas-fir (m^2ha^{-1} in 2002)

$FOLRET_{00}$ = initial (2000) average foliage retention for plot (yrs)

bhage = breast height age in 2002 (yrs)

SI = Bruce's (1981) site index based on intial (2002) conditions (m at 50 yrs)

All variables were highly significant ($p<0.003$), except for SI ($p=0.11$). As expected, Douglas-fir growing stock was the major predictor, and alone it accounted for approximately 74% of the Douglas-fir volume growth; however, growth of the plots also increased as foliage retention increased (Fig. 1). Assuming the healthiest stands were represented by the greatest value of $FOLRET_{02}$ (3.9 yrs), the model implies volume growth losses up to 30% (Fig. 2). The most severely impacted plot had $FOLRET_{02}$ of 1.6. With Douglas-fir basal area set to the population average of 100 ft^2/ac (23 m^2/ha) and average site index of 130 ft (42 m) at 50 yrs, this condition implies an average growth rate of 190 ft^3/ac/yr (13.3 m^3/ha/yr) vs. an expected of 260 ft^3/ac/yr (18.2 m^3/ha/yr) under optimal levels of $FOLRET_{02}$. The inferred cubic volume growth loss for stands experiencing the most severe SNC is therefore approximately 30%, with a population average of 14%

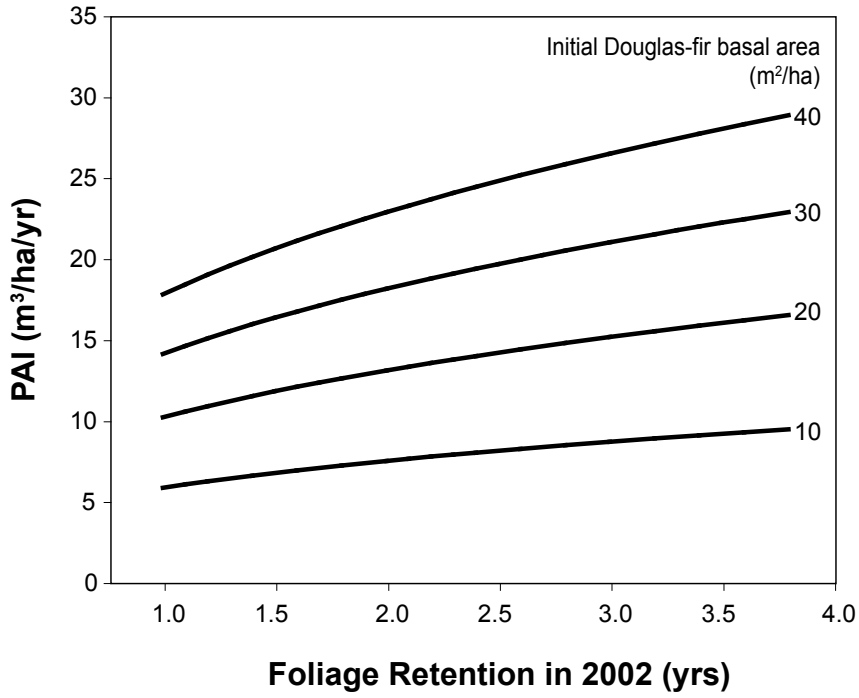

Figure 1. Relationship between cubic volume PAI and SNC severity as measured by foliage retention ($FOLRET_{02}$) for various levels of Douglas-fir growing stock (BA_{DF}). Estimates are for the 2002-2003 growth period, assuming comba=5.6 m^2ha^{-1}, bhage=20 yrs, and SI=42 m.

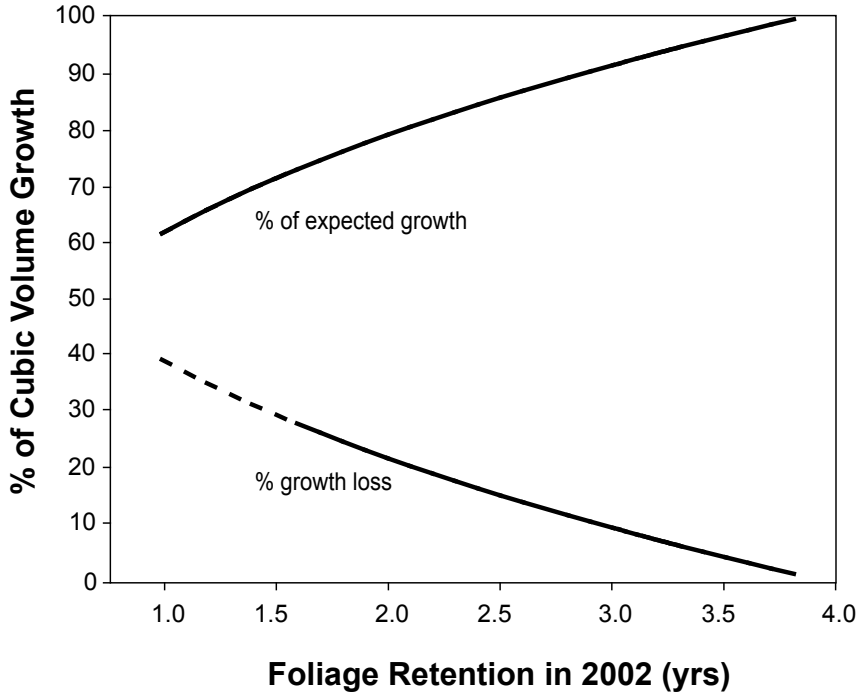

Figure 2. Volume growth losses associated with varying levels of foliage retention ($FOLRET_{02}$) for the 2002-2003 growth period.

loss (average foliage retention of 2.5 yrs).

Growth loss curves from the retrospective phase and the first and second 2-yr growth period were previously reported to be similar in magnitude (Fig. 3). Stands with the most severe SNC in 2002, however, were estimated to reach only 27% growth loss during the subsequent 2-yr growth period. This loss is considerably lower than the maximum losses during the previous growth periods (50-55%).

It was expected that stands experiencing severe SNC would show either a sharper decline or more modest increase in PAI from 1998 to 2003. However, when the curves are standardized by plotting the growth loss as a function of years of foliage loss relative to the plot with greatest foliage retention in that period, growth losses seemed to have peaked in 1998-1999 and 2000-2001, with a low point in the most recent 2002-2003 growing seasons (Fig. 4). Additional analyses for the full 6 years of growth record are currently under way to determine the extent to which cumulative effects of SNC on height growth are imposing lower growth expectations and lower apparently growth losses in 2002-2003. However, site index has been repeatedly found a relatively weak or insignificant variable in the regression analyses, suggesting either that growth losses are not dependent on site quality or that site index is controlled by and correlated with SNC severity, as represented in foliage retention.

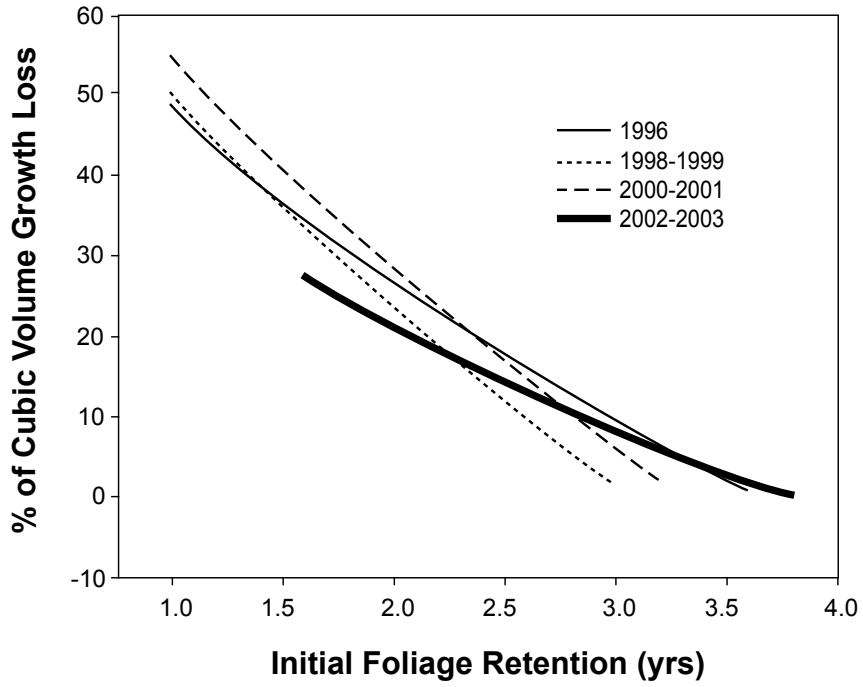

Figure 3. Cubic volume growth loss (%) as a function of foliage retention at the beginning of the growth period for 1998-99, 2000-01, and 2002-2003, and foliage retention in the following spring for 1996.

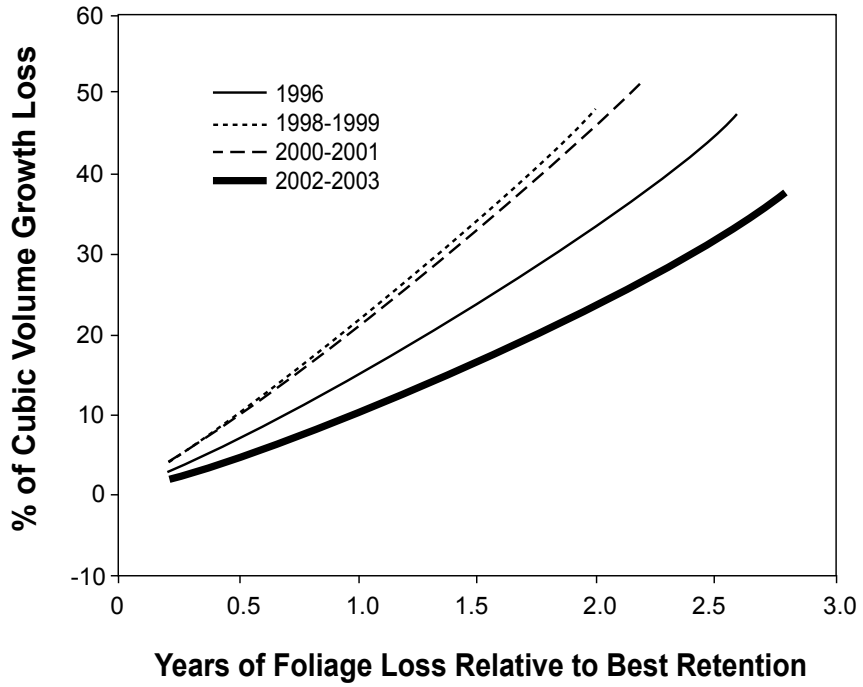

Figure 4. Cubic volume growth loss (%) expressed as a function of years of foliage loss compared to the healthiest plot for each growth period.

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Growth Responses to Pre-commercial Thinning Under Differing Levels of Initial Swiss Needle Cast Severity in North Coastal Oregon

Doug Maguire, OSU, Alan Kanaskie, ODF, and Doug Mainwaring, OSU

Abstract

A study of pre-commercial thinning was established in 1998 to test growth performance under differing initial severities of Swiss needle cast. Plots have now been through their third 2-yr growth period. During this third period, significant block and thinning effects were observed. Even after accounting for initial basal area of Douglas-fir in an analysis of covariance, the thinning effect remained significant, but the effect was positive 200 residual tpa and strongly negative for 100 residual tpa. Block or site effects eliminated foliage retention as a significant factor, but replacing block effects with foliage retention produced similar results, suggesting that foliage retention represents a major portion of the block effect. Growth responses for the 2002-03 growth period indicate that stand growth accelerates after thinning to 200 tpa, but that thinning to 100 tpa may cause a decline in growth for a given level of residual basal area.

Introduction

Concern remains about the possible exacerbating effects of thinning on Swiss needle cast (SNC) and corresponding effects on growth responses. On one hand, reductions in stand density may maintain growth and vigor of residual trees and stands, but on the other hand is anecdotal evidence that thinning does not eliminate or ameliorate the disease but rather weaken the trees further. In some areas, commercially thinned stands with few SNC symptoms have been clearcut several years after thinning due to their apparently rapid decline and intensification of SNC. Similarly, the lack of thinning response in stands with moderate SNC raises the question as to whether stand management objectives normally attainable by thinning can be met under moderate or severe SNC. If thinning does adversely impact tree condition and growth due to intensification of SNC, then alternative strategies must be explored. The objectives of the ongoing pre-commercial thinning study are: 1) to test whether thinning in pre-commercial stands leads to intensification of SNC symptoms, particularly foliage retention; and 2) to test whether thinning in pre-commercial stands with a given initial

intensity of SNC leads to growth rates below those that would be expected under the reduced stand density. This report addresses the second objective.

Methods

In the late winter/early spring of 1998, 22 sets of plots were established across a range in initial Swiss needle cast (SNC) severity. Most of these sets contained a pair of plots, one thinned to 200 tpa and the other a control, but some included a third plot that allowed testing of 100 residual tpa. The original thinning prescription called for leaving 200 tpa (494 tph), but because stand densities were already low on two installations, the target residual was lowered to 100 tph (247 tph). The third plot was established on 5 installations. All control plots and 200-tpa plots were square and covered 0.08-ha (1/5-ac; 31.8 x 31.8 m), except for the two installations on which the thinned plot was reduced to 100 tpa. The control plots matching the latter two 100-tpa plots, as well as all 7 plots thinned to 100 tph, encompassed an area of 0.16-ha (2/5-ac). On each measurement plot, all trees were tagged and measured for diameter at breast height. At least 40 Douglas-fir trees on each plot were also measured for total height and height to crown base. The treated plots were thinned before the growing season started in 1998. After 2, 4 and 6 growing seasons (after the 1998-99, 2000-01, and 2002-2003 growth periods), all trees were remeasured for dbh, and all trees from the original height subsample were remeasured for total height and height to crown base. Where necessary, replacement trees for the height subsample were substituted with another tree of the same diameter. Ten dominant or codominant trees on each plot were also scored for SNC at time of plot establishment in 1998 and during annual visits in the spring (1999-2004).

Factors influencing growth responses in 2002-03 were investigated in three ways: 1) as a randomized block experiment with plot pairs treated as blocks and plots classified as thinned or controls (similar to a paired t-test); 2) as a multiple regression problem with a large number of potential predictors such as initial stand density, thinning intensity, and initial SNC severity; and 3) a randomized block experiment with a large number of potential covariates (analyzed with a multiple regression model).

Results and Discussion

A large portion of plot-to-plot variation in Douglas-fir volume growth (80%) was accounted for by block effects, which would include a wide array of factors such as site index, soil type, initial stand density, Swiss needle cast severity, and many others. As a result, much of the block effect could alternatively be explained directly by specific covariates. Initial Douglas-fir basal area (in the year 2002) was also a fairly strong predictor, alone accounting for 35% of the variability in volume growth. When analyzed as a randomized block experiment with no covariates, both block and treatment effects were significant ($p<0.001$). The treatment (thinning) effect was also significant ($p<0.001$) after correcting for initial Douglas-fir basal area in an analysis of covariance, and with this covariate in the model, thinning to 100 tpa had a very significant negative effect ($p<0.001$) and thinning to 200 tpa had a marginal positive effect ($p=0.07$) on Douglas-fir increment. Needle retention did not explain any significant amount of additional variation in the following model:

$$\ln[PAI] = BLOCK + 0.43350 \ln(BA_{DF}) - 0.39020\, PCT_{100} + 0.14056\, PCT_{200} \quad [1]$$

where PAI = plot-level periodic annual cubic volume growth of Douglas-fir for 2002-2003 (m^3/ha)

BLOCK = set of indicator variables and associated parameter estimates representing the block effect

BA_{DF} = initial Douglas-fir basal area (m^2ha^{-1} in 2002)

PCT_{100} = 1 if plot was thinned to 100 tpa; 0 otherwise

PCT_{200} = 1 if plot was thinned to 200 tpa; 0 otherwise

This model explained 95% of the variation in the logarithm of cubic volume increment. Because retention within a pair or triplet of plots tended to be similar, the block effects were largely accounting

for differences in foliage retention. When block effects were removed, foliage retention was very significant ($p<0.0001$), but the model explained 14% less variation than the models with block effects:

$$\ln[PAI] = -0.40693 + 0.80965 \ln(BA_{DF}) + -0.32964 PCT_{100} + 0.31475 PCT_{200} + 0.68182 \ln(FOLRET_{02}) \quad [2]$$

where $FOLRET_{02}$ = initial (2002) average foliage retention for plot (yrs)and other variables are defined above

All variables were statistically significant (all $p<0.003$), and 81% of the variation in the logarithm of Douglas-fir volume growth was explained by the model. Foliage retention in 2002 ranged from 1.2 to 5.0 yrs, suggesting that plots with the most severe SNC were growing only 38% of the volume that plots with the greatest needle retention were growing (Fig. 1). At a given level of Douglas-fir basal area and needle retention, plots thinned to 200 tpa were growing about 37% more than the unthinned plots, and plots thinned to 100 tpa were growing 39% less. These results suggest that thinning to moderate stocking (200 tpa) will stimulate growth of the residual trees even under severe SNC, but that thinning to lower residual stocking (100 tpa) may lead to growth decline.

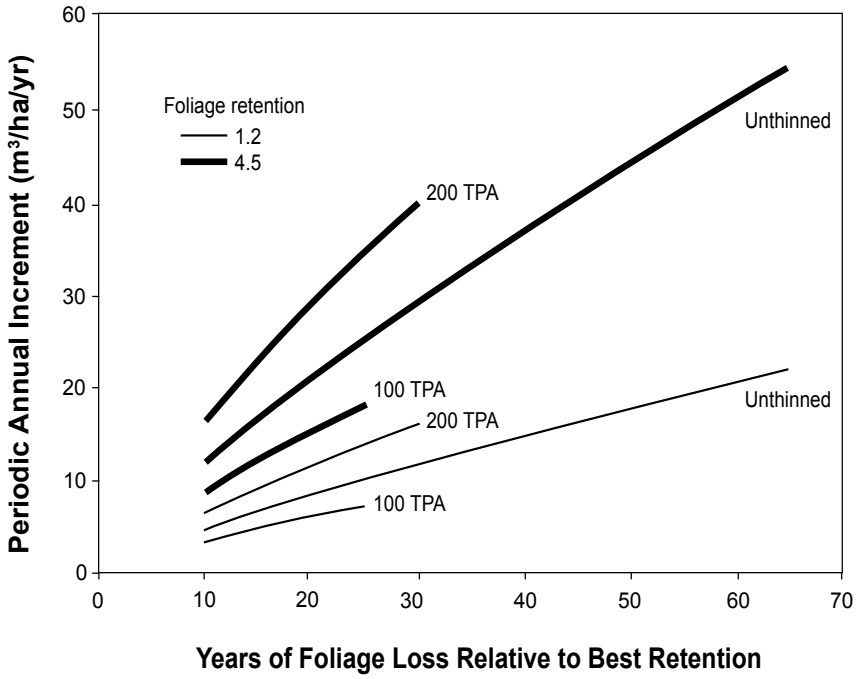

Figure 1. Periodic annual increment as a function of residual Douglas-fir stocking foliage retention level, and residual tpa after thinning (trends estimated from model [2]).

Influence of Stand Development and Intensive Silviculture on Crown Sparseness

Aaron Weiskittel and Doug Maguire, OSU

Introduction

The ratio of live crown length to sapwood area (CLSA) is an effective index of crown sparseness. It is correlated with needle loss caused by Swiss needle cast (SNC) and is much easier to measure directly than years of foliage retention (Maguire and Kanaskie 2002). In addition to SNC, the index is related to tree social position in the stand (Maguire and Kanaskie 2002), but relatively little is known how the index changes through time and and how it is influenced by silvicultural treatments. This analysis examines changes in CLSA through time and in response to treatments such as fertilization, vegetation management, and thinning.

Methods

Study area

Data were collected from four studies, namely studies on precommercial thinning (PCT), SNC growth impact (GIS), vegetation management (VMRC), and thinning plus fertilization (SMC). The PCT and GIS studies have previously been described by Maguire et al. (2003a,b).

The VMRC study was implemented by the Vegetation Management Research Cooperative and consists of two separate installations, one in the mid-Coast Range and the other in the foothills of the Cascades. The study is designed to test the influence of differing levels (4-100 ft^2 of complete vegetation control) and types (complete removal of only herbaceous vegetation and complete removal of only woody vegetation) of vegetation management on Douglas-fir growth and development.

The SMC study made use of of several Stand Management Cooperative installations throughout the Pacific Northwest designed to test the influence of varying silvilcultural treatments on Douglas-fir growth and development. Four SMC installations were used in this analysis, namely Toledo (Oregon coastal), Copper Creek (Washington Cascades), Lewisburg Saddle (Willamette Valley), and Roaring River (Oregon Cascade foothills). Treatments types examined included control, fertilization, fertilization + thinning, and repeated thinning.

Data collection and analysis

In the GIS and PCT studies, ten trees in each 0.08-ha plot were cored for sapwood thickness in both 1998 and 2004. Three to four trees on the 0.04- and 0.4-ha plots for the VMRC and SMC studies, respectively, were also cored for sapwood thickness in 2004. Two cores were taken at breast height on each tree and were perpendicular to plot slope. Finally, tree diameter, total height, and height to crown base were measured.

Multiple linear regression models were constructed for each dataset to test the influence of time and various treatments on the change in crown sparseness index.

Results

PCT plots

Mean 6-yr change in CLSA on the PCT plots was 2.91 ± 2.54 (Figure 1). This change was related to tree diameter at breast height in 2004 (DBH_{04}; p<0.0001), tree height in 2004 (HT_{04}; p<0.0001), the ratio of tree height to diameter (HT/DBH; p<0.0001), initial CLSA ($CLSA_{98}$; p=0.0157), the change in mean stand foliage retention (ΔFOLRET; p<0.0001), and treatment variables (100 TPA, p=0.0096; 200 TPA, p=0.0002). In an average PCT stand, mean CLSA was reduced 30.6 and 25.9% for the 100 TPA and 200 TPA treatments, respectively, when compared to the control plot (Table 2).

Table 1. Attributes of the sample trees used in this analysis.

Variable	Mean	STD	Min	Max
		PCT (n=430)		
DBH_{04} (cm)	25.5	5.6	11.7	45.3
HT_{04} (m)	16.35	5.64	8.94	24.18
HCB_{04} (m)	3.56	2.51	0.10	10.11
$CLSA_{98}$ (cm^2/cm)	2.96	0.94	1.02	7.17
$CLSA_{04}$ (cm^2/cm)	5.88	2.99	1.66	23.52
ΔCLSA (cm^2/cm)	2.91	2.54	-0.31	17.81
AGE_{BH}	14.82	2.15	9.6	19.5
RET_{98}	2.49	0.53	1.10	3.40
RET_{04}	2.89	0.84	1.28	4.60
ΔRET	0.40	0.48	-1.07	1.35
		GIS (n=618)		
DBH_{04} (cm)	29.9	7.9	7.8	57.3
HT_{04} (m)	19.27	4.66	4.87	36.63
HCB_{04} (m)	6.18	3.43	0.01	19.69
$CLSA_{98}$ (cm^2/cm)	5.96	2.39	1.54	17.91
$CLSA_{04}$ (cm^2/cm)	5.71	2.60	1.67	21.37
ΔCLSA (cm^2/cm)	-0.24	2.15	-13.11	9.61
AGE_{BH}	20.64	4.99	11.91	34.92
RET_{98}	2.32	0.34	1.07	3.07
RET_{04}	2.41	0.46	1.47	3.60
ΔRET	0.08	0.35	-0.82	1.01
		VMRC (n=30)		
DBH_{04} (cm)	14.8	2.9	9.8	21.2
HT_{04} (m)	10.55	1.62	7.46	14.67
HCB_{04} (m)	0.85	0.62	0.10	2.34
$CLSA_{04}$ (cm^2/cm)	4.67	1.31	2.97	8.98
RET_{04}	2.35	0.26	1.52	2.91
		SMC (n=54)		
DBH_{04} (cm)	27.1	6.8	12.2	42.7
HT_{04} (m)	18.37	3.07	10.15	23.97
HCB_{04} (m)	6.03	3.41	0.20	12.58
$CLSA_{04}$ (cm^2/cm)	3.85	1.77	1.19	12.35
AGE_{BH}	17.1	3.1	12.5	19.0
RET_{04}	2.69	0.26	2.31	3.27

GIS plots

Mean 6-yr change in CLSA on the GIS plots was -0.24 ± 2.15 (Figure 2) and was related to DBH_{04} (p<0.0001), HT_{04} (p<0.0001), HT_{04}/DBH_{04} (p<0.0001), $CLSA_{98}$ (p<0.0001), mean stand 2004 foliage retention (RET_{04}, p=0.0002), % basal area in Douglas-fir ($\%BA_{DF}$; p<0.0001), mean stand breast age in 2004 (AGE_{BH}; p<0.0001), the cosine transformation of aspect (COSA; p<0.0001), and the interaction between RET_{04} and COSA (p=0.0037). A positive change in CLSA was associated with an increase in DBH_{04}, HT_{04}/DBH_{04}, and AGE_{BH} as well as a decrease in HT_{04}, $CLSA_{98}$, RET_{04}, and $\%BA_{DF}$. A positive change in CLSA was also correlated with northern aspects. However, the effect of aspect was dependent on stand mean foliage retention.

SMC

CLSA did not differ between installations, with a mean of 3.71 ± 1.74. Neither thinning nor fertilization influenced CLSA after accounting for DBH_{04}, HT_{04} and

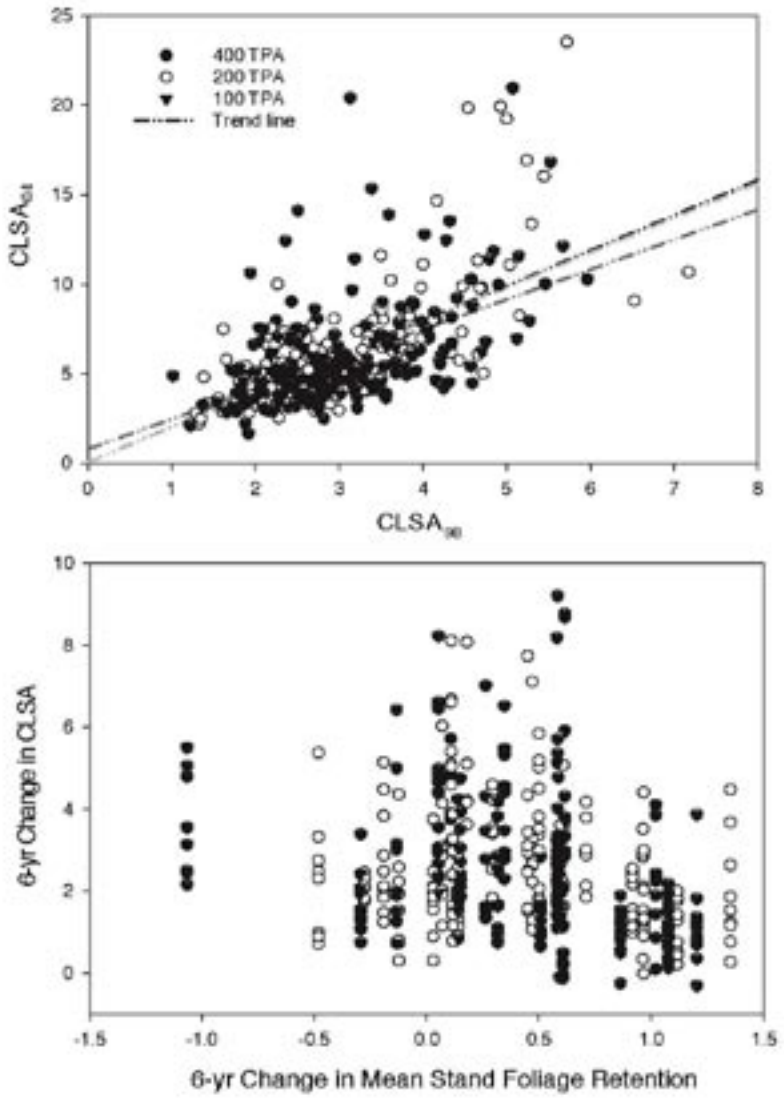

Figure 1. *Crown sparseness index from 1998 to 2004 on PCT plots. Graph A (top) depicts 2004 estimate of crown sparseness over 1998 estimate of crown sparseness for each to the treatments 400 TPA (dark circles), 200 TPA (open circles), and 100 TPA (dark triangles). Graph B (bottom) is the change in crown sparseness over the change in stand mean foliage retention for each treatment.*

Table 2. Model forms, R^2, and root mean square errors (RMSE) for equations presented in this analysis.

Model	Equation form	R^2	RMSE
Change in PCT CLSA (full model)	$\Delta CLSA = -10.4744 + 0.4466*DBH_{04} - 0.9571*HT_{04} + 29.6814*HT_{04}/DBH_{04} - 0.3426*CLSA_{98} - 1.0804*FOLRET - 0.8729*T100 - 0.7381*T200$	0.58	1.64
Change in PCT CLSA (reduced model)	$\Delta CLSA = 1.5138 + 0.8291*CLSA_{98} - 2.6186*T100 - 1.7596*T200$	0.27	2.18
Change in GIS CLSA (full model)	$\Delta CLSA = -6.2421 + 0.2843*DBH_{04} - 0.6535*HT_{04} + 24.5144*HT_{04}/DBH_{04} - 0.8922*CLSA_{98} - 0.6072*RET_{04} - 1.5186*\%BA_{DF} + 0.0963*AGE_{BH} + 1.6979*COSA - 0.5288*(RET_{04}*COSA)$	0.45	1.59
change in CLSA (reduced global model a)	$\Delta CLSA = 3.4296 - 0.5022*CLSA_{98}$	0.19	2.50
change in CLSA (reduced global model b)	$\Delta CLSA = 6.6745 - 0.5609*CLSA_{98} - 1.2398*RET_{98}$	0.22	2.45

HT_{04}/DBH_{04}. The model had an R^2 of 0.89 and a root mean square error (RMSE) of 0.60. Similarly, foliage retention showed no relationship with either thinning or fertilization after accounting for block effects.

VMRC plots

CLSA did not differ between VMRC installations, with a mean of 4.48 ± 0.96. Vegetation management had no influence on the CLSA after accounting for HT_{04}/DBH_{04} and tree foliage retention (TRET). The model accounted for 78.1% of the original variation in CLSA and had a RMSE of 0.69. Also, foliage retention showed no relationship with any type of vegetation management after accounting for block effects.

Discussion

As was found by Maguire and Kanaskie (2002), crown sparseness was was significantly influenced by tree social position, represented by the height to diameter ratio in this analysis. Mainwaring et al. (2004) were only able to detect a marginally significant ($p \approx 0.08$) decrease in the index due to fertilization. Although CLSA appeared to be unaffected by intensive silvicultural treatments such as vegetation management and repeated fertilization in this analysis, it was influenced by several other factors including stand composition and developmental stage. This result is consistent with the small amount of variation in 6-yr CLSA change explained by initial CLSA and change in foliage retention. The influence of species composition and aspect may be

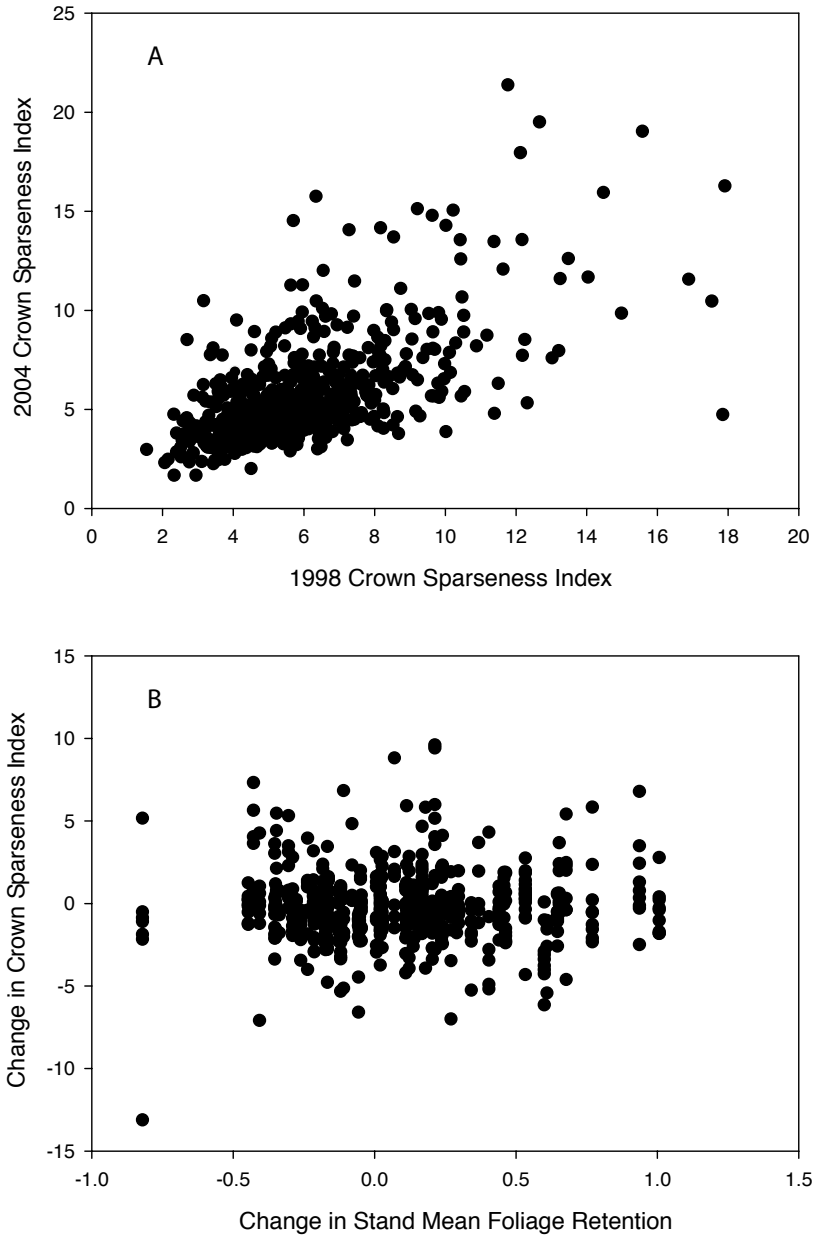

Figure 2. Crown sparseness index from 1998 to 2004 on the GIS plots. Graph A (top) depicts 2004 estimate of crown sparseness over 1998 estimate of crown sparseness. Graph B (bottom) is the change in crown sparseness over the change in stand mean foliage retention.

related to true changes in foliage density, or to differences in needle area to sapwood area ratios related to differing heartwood formation rates (Weiskittel and Maguire 2004). The significant decrease in CLSA after precommercial thinning supports the emerging trend of improved needle retention in the thinned plots (Maguire et al. 2003a).

Although crown sparseness index may be influenced by other factors than foliage loss from disease it is much less variable than foliage retention and is well correlated with several important tree physiological features such as needle size, total tree leaf area, and the tree relative foliage age class distribution (Weiskittel 2004).

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Fungicidal Control of Swiss Needle Cast in a 20-year-old Forest Stand

Jeffrey Stone, OSU; Paul Reeser, OSU; Alan Kanaskie, ODF

Abstract

Annual spray applications of chorothalonil fungicide were carried out over five consecutive years from 1996 – 2000 in a Douglas-fir forest stand. Fungicide applications reduced infection levels of *Phaeocryptopus gaeumannii* compared to the unsprayed stands in foliage sampled in 2001. Total needle retention was also increased in the fungicide spray treatment in 2001. Effects of fungicide spray on *P. gaeumannii* levels persisted in foliage produced in 2001, which did not receive fungicide treatment but had lower infection levels in the treated stands due to reduced inoculum levels compared to the unsprayed stands. Incidence of infection in the 2000 and 2001 foliage sampled in spring of 2002 was near 100% in the fungicide treated plots. Differences in total infection between fungicide treated plots and untreated controls were slight, suggesting that residual effects of fungicide treatment were short-lived. Foliage from the same plots was again sampled in spring of 2003 and 2004. Needle retention remained greater for the treated vs the untreated stands in 2004. Trees in treated stands retained 10 to 50% of the 2000 needle cohort (four-year-old needles) and 25 to 60% of the 2001 cohort in spring 2004. Overall infection levels averaged over four foliage age classes (2000 – 2003) remained significantly lower in the fungicide treated plots. Infection levels in 2001 foliage sampled in 2003 (two-year-old needles) were again significantly less than in the unsprayed plots. Infection levels were not significantly different for 2002 foliage sampled in 2003, or for 2003 foliage sampled in 2004 (one-year-old needles), suggesting that the residual effect of fungicide treatment on inoculum reduction lasted only 2 years.

Introduction

Although the pathogen *Phaeocryptopus gaeumannii* is widely distributed on Douglas-fir in western Oregon and Washington, extensive and severe Swiss needle cast disease (SNC) has not been the historical norm. Severe SNC symptoms have been observed in the western Coast Range from about 1990. Management options for controlling SNC in forest plantations are very limited at present, and the potential for control of SNC by fungicides has not received much attention in the United States. The disease is controlled in

Christmas tree plantations by the fungicide chlorothalonil (Chastagner and Byther 1982, Skilling 1981, Hadfield and Douglas 1982). Annual applications of chlorothalonil are recommended beginning three years prior to planned harvest for marketable Christmas trees (Chastagner and Byther 1982). However, because of the longer duration of protection needed for Douglas-fir rotations, aerial fungicide sprays have not been considered an economically effective option for control of SNC in forest plantations.

Whether SNC can be controlled in forest plantations by aerial applications of fungicides is not known. 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, handspraying the same material at the same concentration reduced incidence of infection to below 42% compared to 100% in unsprayed control (Hood and van der Pas 1979). Some aspects of *P. gaeumannii* biology suggest that annual spray applications throughout a rotation might not be necessary for disease control. Needles are susceptible to infection only during their first growing season. Needles more than one year old are not susceptible to new infection by ascospores (Stone et al 2000). Therefore, needles only need to be protected 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 four to five years. Effective spray applications for two or three consecutive years could therefore eliminate or significantly reduce levels of infection and inoculum production. New, unprotected foliage produced in subsequent years could become infected from residual infections or from outside sources of inoculum.

If fungicide sprays are successful in reducing infections below a critical level, and thereby reducing the inoculum load, SNC might be controlled for several years beyond cessation of fungicide application in treated stands without additional fungicide applications. The amount of time before infection levels return to high levels would depend on the effectiveness of the fungicide spray, residual infection levels, proximity and severity of inoculum sources to the treated stands, and local environmental conditions favoring infection. Furthermore, most Douglas-fir trees can tolerate a low to moderate level of infection without developing symptoms of SNC. While it is probably impossible to completely eliminate *P. gaeumannii* from a forest stand by fungicide sprays, reducing and maintaining infection to below harmful levels may be possible.

This study was undertaken to determine whether a program of aerial fungicide spraying is effective in reducing infection levels of *P. gaeumannii* in forest stands, and how long the residual effect of fungicide treatment is maintained after the cessation of five consecutive annual fungicide treatments. This study was done in cooperation with the Oregon Department of Forestry, which treated study sites with annual aerial applications of Bravo fungicide between 1996 – 2000. Foliage produced in spring 2001 was the first year of untreated foliage in the fungicide treated stands. Foliage was collected in the spring of 2003 and 2004 and the 2001, 2002, and 2003 needle cohorts were sampled.

Materials and Methods

Study sites

Aerial sprays were applied to a study site established by the Oregon Department of Forestry near Beaver, OR. The plantation was established in 1980 and was characterized as severely diseased in 1995. Bravo Weatherstik 720 fungicide was applied at the rate of 5.5 pt/30 gal/acre by aerial spray to three five-acre plots for five consecutive years, 1996-2000. Sprays were applied shortly after bud break, with shoots averaging 1 – 3 in. Adjacent unsprayed five-acre plots were designated controls.

Sampling

Two transects were established in each of three plots that received fungicide treatment and three unsprayed control study plots. Transects were oriented perpendicular to each other and crossed the plots from edge to edge from approximately the mid point of each side. Sampling points were located at approximately 100 ft intervals along each transect starting at approximately 50 ft in from the plot edge. Each transect had 6 sample points except in plot T3, a long narrow plot, which had 8 points in one transect and 4 in the other. Two trees were sampled at each sample point, two secondary lateral branches were cut from the

fifth to seventh whorl from the top. Needle retention on the sampled branches was assessed in the field, then branches were placed in bags and returned to the lab for infection assessments. Samples were collected from stands C1, C2, T1, and T2 in May 2001 and 2002, and from all six stands in May 2003 and May 2004.

Assessment

Needle retention was rated on a scale of 1-9, where 9 = 90-100% needles retained, for each internode starting with the current year (2001 foliage). Retention ratings for each internode (1997-2000) were summed to obtain a composite retention index for each branch. Needles were removed from internodes by age class, placed in envelopes and stored frozen (-20 C). Three samples of ten needles /age class/branch/tree were randomly drawn for quantitative PCR analysis (Winton et al. 2002). A sample of 50 needles/age class/branch/tree was randomly drawn for pseudothecia counts. Needles were affixed abaxial side up to index cards with double-sided adhesive tape. Cards were examined under dissecting microscopes to determine the proportion of needles bearing pseudothecia (incidence of infection). The first ten needles on each card with pseudothecia present were then used to determine pseudothecia density, or 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, tip) of each of the ten needles was determined. Infection index, the product of incidence and pseudothecia density, was used as a response variable for comparisons of treatments. Since incidence of infection was near 100% for all plots, infection index mainly reflects differences in amount of pseudothecia on needles. Statistical analyses were performed with SAS for Windows Vers. 8 (SAS Institute, Cary, NC) and Statgraphics (Manuguistics Inc, Rockville, MD).

Results

For foliage sampled in May, 2001, which had been treated for five consecutive years, needle retention was significantly greater in stands that had been treated with Bravo for five years ($p < 0.05$, Table 1). The average retention index for treated plots, 27.3, represents approximately 75% of foliage in age classes 1-4 retained compared to about 40% for the unsprayed control stands. The distribution of needles retained in the two treatments is shown in Figures 1 and 2. Nearly all current year needles were retained in both treatments. Nearly all 1999 needles were also retained in the Bravo treated plots, but only about half of this complement was retained in the unsprayed control plots. 70-80% of 1998 needles were retained in the treated plots compared to less than 10% for the control plots. A small proportion of 1997 needles remained on the treated trees but this complement was completely absent from the unsprayed trees. For the foliage sampled in 2004, again nearly all one-year-old foliage (2003 cohort) needles were retained for both the sprayed and unsprayed

Table 1. Mean needle retention indices for treated and control stands. Indices are the sum of needle retention ratings for each of four internodes, 1997–2000 for foliage sampled in May 2001 and 2000-2003 for foliage sampled in May 2004.

Plot	Composite Retention Index	
	2001	**2004**
T1	28.7	28.0
T2	NS	19.5
T3	25.8	20.4
C1	15.9	19.4
C2	NS	18.6
C3	12.4	14.3

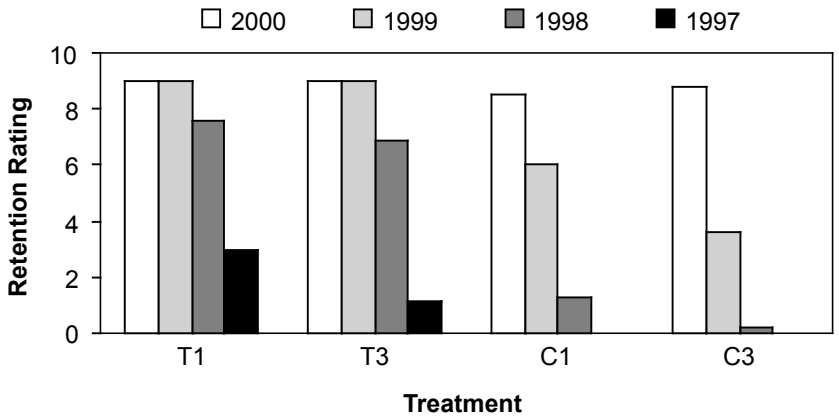

Figure 1. Comparison of needle retention ratings for plots treated with Bravo fungicide for 5 years (T1, T3) and unsprayed (C1, C3). Ratings are based on field assessment of needle retention for each internode on secondary lateral branches taken from between the 5-7th whorl from the treetop in May 2001.

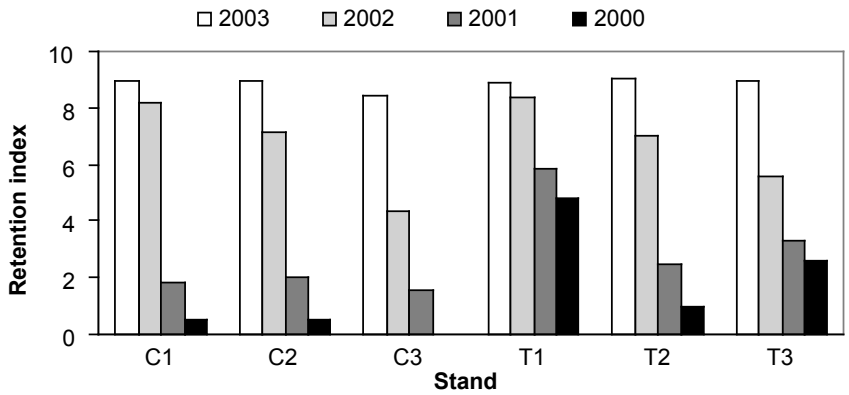

Figure 2. Comparison of needle retention ratings for stands treated with Bravo fungicide for 5 years (T1, T2, T3) and unsprayed (C1, C2, C3). Ratings are based on field assessment of needle retention for each internode on secondary lateral branches taken from between the 5-7th whorl from the treetop in May 2004.

stands. The Bravo treated stands still retained a greater proportion of the three- and four-year-old needles than the unsprayed stand (Table 1, Figure 2).

Quantitative PCR (QPCR) analysis of foliage sampled in May, 2001 showed significant differences in levels of *P. gaeumannii* in foliage for age classes 1998-2000 (Table 2). There were too few 1997 needles present in the control plot trees for this age class to be included in the analysis. QPCR values for both fungicide sprayed plots were significantly lower than foliage from unsprayed controls for all three-age classes sampled.

Differences between fungicide sprayed and control treatments persisted through the first year that aerial fungicide sprays were not applied to the treatment plots. Foliage that emerged in June 2000 was the last age class to be treated with fungicide spray. Age class 2000 foliage from fungicide treated plots had one-half to one-third the level of infection (infection index, NFX) present in the unsprayed control at two years following emergence (Table 3). 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. Infection levels in 2001 foliage in plot C1 (unsprayed) were not statistically different from the two sprayed plots (Table 3).

Incidence of infection, the proportion of needles bearing at least one pseudothecium, measured in May, 2002 was near 100% for fungicide sprayed as well as unsprayed plots for both age classes, indicating virtually all needles in both treatments and both age classes were infected. Incidence of infection was also near 100% for all needle age classes and treatments in foliage collected in 2003 and 2004. Differences in infection index (NFX) therefore reflect differences in the abundance of pseudothecia (Tables 3, 4). Nearly all one-year-old needles (2001 needles) in the 2002 sample were infected regardless of treatment, but the amount of infection in fungicide sprayed plots was slightly less than for unsprayed plots (Table 3). Pseudothecia levels in one-year-old needles (2002) collected in spring of 2003 from the fungicide treated plots, however, were not statistically different from the unsprayed plots. There were no significant differences in infection index between foliage from sprayed and unsprayed stands for the 2004 sample (Table 4).

Figures 3 and 4 show the trend of infection levels in two- and

Table 2. Comparison of quantitative PCR values (ng *P. gaeumannii* DNA/pg Douglas-fir DNA) for foliage for fungicide sprayed and unsprayed plots measured in May, 2001. Letters in the same column indicate different groups at $p < 0.05$.

	Needle Age Class		
Treatment	2000	1999	1998
C1	2.40 b	2.18 b	2.17 b
C3	2.56 b	2.38 b	2.22 b
T1	0.79 a	1.05 a	1.18 a
T3	0.28 a	0.46 a	1.14 a

Table 3. Comparison of infection index (incidence x pseudothecia density) for foliage collected in May 2002. Letters in the same column indicate different groups at $p < 0.05$.

Plot	2001 Needles	2000 Needles
C1	0.12 b	0.30 b
C3	0.18 a	0.46 a
T1	0.08 b	0.14 c
T3	0.10 b	0.15 c

one-year-old foliage in fungicide treated plots gradually approaching levels in the untreated checks. Infection levels in two-year-old foliage from the fungicide treated stands were significantly lower than in the unsprayed stands in 2002, reflecting fungicide treatment of the foliage cohort produced in spring of 2000. Infection levels were also lower in two-year-old needles sampled in 2003, reflecting the lower infection seen in this needle cohort (2001) one year after treatment ceased (Table 3), but the difference between sprayed and unsprayed plots was less than for 2002 (Figure 3). Infection levels in one-year-old foliage from fungicide treated plots were lower than from the unsprayed plots in 2002, but treatments were not different in 2003 or 2004 (Figure 4).

Table 4. Comparison of infection index (incidence x pseudothecia density) for foliage collected in May 2003 and May 2004. Letters in the same column indicate different groups at p <0.05.

Stand	One-year-old	Two-year-old	Three-year-old
2003 sample	**2002 Needles**	**2001 Needles**	**2000 Needles**
C1	0.20 ABC	0.44 B	0.48 B
C2	0.15 A	0.40 B	0.50 B
C3	0.25 C	0.55 A	0.25 AB
T1	0.14 A	0.33 B	0.33 A
T2	0.16 AB	0.35 B	0.35 A
T3	0.21 BC	0.41 B	0.30 A
2004 sample	**2003 needles**	**2002 needles**	**2001 needles**
C1	0.07	0.25	0.20
C2	0.11	0.29	0.29
C3	0.13	0.25	0.16
T1	0.12	0.22	0.19
T2	0.11	0.27	0.25
T3	0.14	0.29	0.28

Discussion

Fungicide applications for five consecutive years resulted in concurrent reduction of *P. gaeumannii* infection and significantly greater foliage retention in the Bravo sprayed compared to the unsprayed plots. Needle retention in current year needles was not different between sprayed and unsprayed plots, as expected. However, increased retention of the two- and three-year old needles resulted in retention of approximately one additional years' cohort of foliage in the sprayed vs. unsprayed plots in 2001, reflecting the effects of fungicide treatment on disease control. A separate analysis of wood characteristics from these plots showed that untreated control trees also have lower wood moisture content, decreased ring width, and increased latewood proportion compared to fungicide treated trees, characteristics that have been attributed to reduced vigor and defoliation due to disease (Johnson et al 2001). Taken together, these results reinforce the conclusion that *P. gaeumannii* is the primary agent responsible for the current decline of Douglas-fir in western Oregon and Washington. A separate analysis of growth differences from this study is in progress.

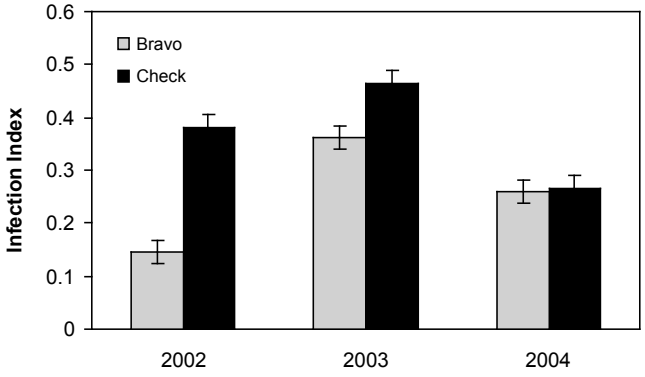

Figure 3. Comparison of infection index in two-year-old needles sampled in 2002, 2003, and 2004. Age class 2000 needles, which were two-years-old when sampled in 2002, were the last needles to receive fungicide treatment. Age class 2001 needles sampled in 2003 were not treated with fungicide, lower infection levels indicate the residual effect of fungicide treatment on inoculum levels in the fungicide treated plots.

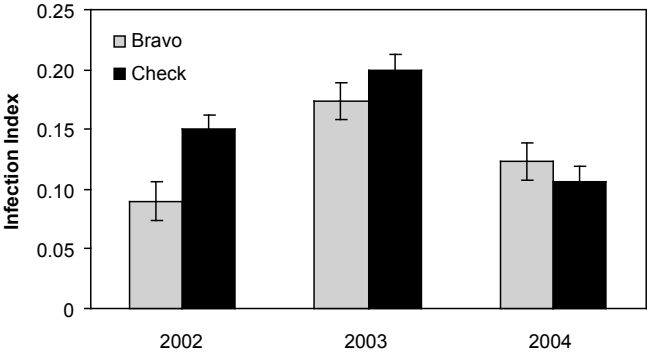

Figure 4. Comparison of infection index in one-year-old needles sampled in 2002, 2003, and 2004.

Foliage from fungicide treated plots had significantly lower levels of *P. gaeumannii* than unsprayed controls in 2001 foliage measured in May, 2002. Since this foliage had not been sprayed with a protectant fungicide, lower infection levels in this age complement must reflect reduced inoculum levels resulting from multiple year treatment in the fungicide-sprayed plots. However, it appears that differences in infection levels between sprayed and unsprayed plots after multi-year treatment were already beginning to converge in this first cohort of foliage not protected by fungicide. Infection levels in both treatment plots were significantly different from only one of the unsprayed control plots.

Infection levels in the fungicide treated plots continued to converge toward levels in the untreated checks in 2003 and 2004. Infection levels in the one-year-old 2002 foliage from the two treatments were not statistically different. This suggests that even after five consecutive years of fungicide applications, sufficient residual infection remained in the stands to enable infection levels to rapidly build up in only two years after the cessation of fungicide treatment.

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, coverage, and timing. In this study, the amount of residual infection appears to be relatively high. Chlorothalonil has proved effective in controlling SNC in Christmas trees (Chastagner and Byther 1983) and forest plantations (Chastagner and Stone 2001). The WeatherStik formulation of chlorothalonil (Daconil) provided superior control to other formulations (Chastagner and Stone 2001).

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*. 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 the fungicide treatment reduced the amount of infection in these needles, there was still sufficient successful infection to effectively saturate foliage. Pseudothecia density in the sprayed plots was one-third to one-half that of the untreated control and accounted for the observed differences between treatments. One reason for this may be the exceptionally high level of disease at this site. 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.

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, handspraying the same material at the same concentration reduced incidence of infection to below 42% compared to 100% in unsprayed control (Hood and van der Pas 1979). The success of the handspray application was attributed to superior foliage coverage and greater amounts of material applied. Handspray applications were applied to run off by a person climbing within the tree crowns. This highlights the difficulty of achieving sufficient aerial application rates in forest tree stands compared to Christmas trees, where SNC is routinely controlled by fungicide. The relatively high amount of residual infection present in the fungicide treated plots in our study suggest that coverage may have been inadequate. Fungicide application volumes for forestry should probably be adjusted based on stand age and foliage area rather than a standard rate per acre. It is also possible that the level of disease at this site was too severe, and that aerial fungicides might be more effective in controlling SNC at sites with more moderate levels of disease.

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Microsatellite Population Structure of *Phaeocryptopus gaeumannii* and Pathogenicity of *P. gaeumannii* Genotypes/Lineages

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Introduction

We recently completed an SSCP survey of allelic variability in slowly evolving genes for 30 populations of *Phaeocryptopus gaeumannii* (Winton 2001). We found that *P. gaeumannii* in the region of Oregon's Swiss needle cast epidemic is subdivided into two reproductively isolated sympatric lineages. Lineage 1 has nearly worldwide distribution, occurring throughout much of the Pacific Northwest as well as in exotic locations that have historical reports of disease. Lineage 2 is restricted to Oregon's coastal forests. This latter lineage was frequently isolated from diseased stands in Tillamook County and was extremely common near Gold Beach and in forest trees growing adjacent to the Oregon Department of Forestry D.L. Phipps Forest Nursery.

The distribution suggests that the second lineage may be derived from southern Oregon. Furthermore, the most severely diseased plantations in Hansen et al (2000) were also found to have the highest incidence of this lineage. These plantations are owned by the Oregon Department of Forestry and may have been planted with stock from the Phipps Nursery. If so, it is possible that the dissemination of infected seedlings grown in southern Oregon to plantations in the conductive environment along the North Coast may have helped establish the current epidemic by the introduction of new genotypes. These data suggest that a wider longitudinal and latitudinal sampling should clearly demonstrate whether one lineage is from the north and the other from the south.

The objective of this study is to confirm the proposed the origins of the two lineages and estimate the outcrossing rate within lineages. A secondary objective is to further characterize *P. gaeumannii* populations surrounding forest nurseries in southern Oregon. The discovery by Winton (2001) that *P. gaeumannii* in the Pacific Northwest actually comprises two reproductively isolated lineages, or cryptic species, suggested that differences in pathogen virulence may be an important factor in the current decline of coastal Douglas-fir due to Swiss needle cast. Winton (2001) also provided evidence of variation in pathogenicity among strains of *P. gaeumannii* on Douglas-fir seedlings. One strain, isolated from the severely diseased Juno Hill site, caused significantly greater needle loss than

strains derived from less damaged sites. This study was conducted to determine whether genotypes or lineages of *P. gaeumannii* differ in their ability to cause disease.

Methods

Microsatellite marker development

Approximately 10 ug of total genomic DNA from a single *P. gaeumannii* isolate was fragmented separately with the restriction enzymes BstUI and RsaI. Doubled-stranded synthetic linker oligonucleotides of known sequence were then attached to the restriction fragments via blunt-end ligation. Restriction fragments were then hybridized to biotinylated synthetic microsatellite oligonucleotides that were covalently attached to magnetic microspheres. The beads were then washed in succesively stringent conditions such that the restriction fragments were enriched for those containing microsatellite sequences. PCR with a linker sequence primer was performed on the final elutant to increase the amount of microsatellite enriched DNA such that it could be cloned for DNA sequencing. Sequences were examined for microsatellites and the most promising (long, perfect repeats) were chosen for primer design. Of the 16 primer sets designed, 10 were suitable for population studies. Each *P. gaeumannii* isolate was PCR amplified at each of the 10 loci. DNA fragments were separated by capillary gel electrophoresis on an ABI prism 3100 in GeneScan mode (Applied Biosystems). Allele sizes and repeat numbers were estimated and evaluated for quality in GenoTyper (Applied Biosystems). Data was exported in spreadsheet format to construct the genotype database.

Population Sampling

Because ascospores are dispersed by wind and rain, a population was arbitrarily defined as a single plantation or stand of the Douglas-fir host. Our original culture collection consisted of 17 populations of the coastal form of Douglas-fir within the native range of Douglas-fir in western Oregon and Washington. Ten of these were within the main epidemic area of Oregon's Coast Range (between Waldport and Astoria within 18 miles of the coast), four of which were mature stands at least 80 years old. All other stands in the study were between the ages of 10 and 25. Seven of the native coastal form populations were located outside of the main epidemic area. One population from New Mexico represented a natural stand of the interior form of Douglas-fir. Because the fungus has previously caused disease only where Douglas-fir was planted as an exotic species, we also sampled 12 locations outside of the natural Douglas-fir range where there had previously been reports of disease. We have added to our existing collection of isolates an additional 10 populations in the Oregon Cascade Range and 5 populations in northern Idaho and eastern Washington. In addition, we have sampled an additional year at 8 of our 9 SNC monitoring plots. Single isolates were obtained from 5 to 21 trees per stand; a total of 1350 isolates are being tested. In total, 13,350 individual loci (10 loci X 1350 individuals) have to be examined for accuracy before they can be assembled into the database.

Trees selected for sampling were non-adjacent and haphazardly chosen within a stand with no regard to apparent disease level. Branches with foliage bearing pseudothecia were collected in the spring of 1997, transported to the lab, and prepared for isolation. Single-ascospore P. gaeumannii isolates were obtained by adhering 10-50 needles bearing only P. gaeumannii pseudothecia to lids of petri plates containing water agar to allow ascospore discharge on the agar surface. Needles were arbitrarily selected from the most recent needle cohort bearing mature pseudothecia. Samples were incubated in a moist chamber for 3-5 days at 17 °C and one individual ascospore per host tree was removed from the agar surface with a heat-drawn Pasteur pipette. Isolates were grown at 17 °C for 3-5 months on potato dextrose agar (Difco Laboratories, Detroit, MI).

Pathogenicity comparisons

Plug-1 Douglas-fir seedlings of the "Burnt Woods" seed source were provided by Starker Forests. Seedlings were transplanted in a soil/peat/perlite potting mix in one gallon pots. Prior to inoculation, seedlings were preconditioned for two weeks in a growth chamber at 18C, 85% RH, 12 hour photoperiod. Seedlings were maintained under the same conditions for 14 days following inoculation, then transported to the OSU Botany field lab. *P. gaeumannii* cultures

were isolated from single ascospores and maintained as stock cultures on Potato Dextrose Agar. Inoculum was prepared from cultures of each isolate grown in stationary culture in 1L Erlenmeyer flasks containing 250 ml Potato Dextrose Broth. Inoculum cultures were harvested at approximately 60 days. The mycelium was filtered through nylon mesh, fresh weight determined, and added to a measured volume of 0.05% water agar to give a concentration of 0.02 g mycelium/ml. The mycelium was then fragmented with a tissue homogenizer (Brinkman Instruments). A sample of each inoculum was serially diluted and plated on potato dextrose agar to assess the viable fragments per ml. Inoculum was applied to seedlings in the growth chamber by means of an airbrush spray apparatus. Each seedling received 25 mL (0.5 g) of inoculum. Ten seedlings per treatment group were inoculated with a single isolate from each of 7 SSCP genotypes present in Oregon and one of the two genotypes present in the eastern United States.. A control group was inoculated with killed *P. gaeumannii* mycelium. Needle retention was measured the following year and ANOVA used to evaluate whether symptom development differentiated between the two lineages or was restricted to specific genotype(s).

Results and Discussion

Population structure

Microsatellite genotyping and preliminary analysis has been completed for 854 isolates at all 10 loci. Another 476 isolates have been genotyped and integrated into the database but not yet analyzed.

Preliminary analyses of the isolates for which we have complete data confirm the presence of the two lineages found by SSCP (Figure 1). Furthermore, isolates from Vermont, New York, and New Mexico, a putative third lineage by SSCP, appear scattered within lineage 1. Gene diversity statistics within lineages for each population (stand) are presented in Tables 1 & 2. These statistics were not available with the more conservative SSCP method that was originally used to distinguish the two *P. gaumannii* lineages (Winton et al 2001). In general, lineage 1, with worldwide distribution, displays lower gene diversity in populations where Douglas-fir was planted as an exotic (Figure 2). This would be expected if the genetic diversity of the founding population was initially low and later gene flow was restricted. These results are consistent with the hypothesis of reduced diversity in small populations due to founder events and genetic drift. High levels of gene diversity were found where Douglas-fir is native, both in young plantations and mature stands, as expected. More than half of the native populations have a gene diversity above 0.5.

Genetic relationships among populations of lineage 1 are depicted in Figure 3. All of the populations in Oregon's Coast Range clustered together. But notice the populations labeled in grey. These are forest nurseries outside of the area that may have provided seedlings for many of these plantations. This tree also suggests possible founding populations for several

Figure 1. Genetic relationships among isolates.

Table 1. Basic population genetic statistics for lineage 1. Ordered by increasing gene diversity.

Population	Sample size	Gene Diversity	Gene Diversity Standard Deviation	No Alleles	No Alleles SD
Italy	17	0.0000	0.0000	1.00	0.00
5Switzerland	20	0.0833	0.0167	1.83	0.41
Germany	13	0.0855	0.0855	1.33	0.82
NewZealandN	16	0.1014	0.0486	1.83	0.98
3Switzerland	7	0.1825	0.0890	1.67	0.82
NewZealandS	11	0.2424	0.1138	2.17	1.17
NewYork	11	0.2485	0.1208	2.00	1.26
Canby	5	0.2667	0.1333	1.67	0.82
UK	15	0.3143	0.1227	2.50	1.52
France	14	0.3242	0.1081	2.50	1.22
1Switzerland	8	0.3452	0.1270	1.83	0.75
SanJuanWA	19	0.3489	0.0591	3.00	0.89
4Switzerland	5	0.3667	0.1687	2.00	1.26
Phipps	3	0.3889	0.1809	1.67	0.82
3Idaho	9	0.3935	0.1437	2.67	1.63
Vermont	16	0.4083	0.0818	2.83	2.04
CoalOld	6	0.4222	0.1056	2.17	0.75
2Idaho	14	0.4451	0.1183	4.17	3.43
NorthFork	14	0.4542	0.1278	3.17	1.94
1Idaho	10	0.4556	0.1279	3.17	1.72
29Casc	12	0.4571	0.1349	3.17	1.72
MacDonaldForest	15	0.4619	0.0955	4.17	1.94
Olympia	17	0.4681	0.1112	3.17	1.94
Upper	22	0.4776	0.1008	4.00	2.68
Spokane	16	0.4889	0.1325	4.83	3.43
ToledoWA	18	0.4891	0.1134	4.00	2.53
27Casc	15	0.4937	0.1013	4.33	2.07
EdwardsOld	5	0.5167	0.1167	2.17	0.75
JunoHill	15	0.5254	0.1241	4.33	2.50
Acey	17	0.5404	0.1170	4.50	1.76
30Casc	9	0.5463	0.0866	2.67	1.21
DriftCreek	8	0.5476	0.1139	2.67	1.03
Salal	10	0.5593	0.1167	3.50	1.64
BixbyOld	11	0.5727	0.1011	4.33	2.50
NewMexico	5	0.5833	0.0910	2.50	0.84
CoalCreek	17	0.5833	0.1237	4.33	2.50
42Casc	11	0.5848	0.1145	4.00	2.10
Lower	16	0.6028	0.1009	4.83	3.19
PrairieOld	5	0.6167	0.0910	2.67	1.21
FosterDam	10	0.6222	0.0422	3.33	1.03
37Casc	8	0.6310	0.0637	3.33	0.82
Limestone	28	0.6380	0.0890	7.00	2.68
CedarNorth	2	0.6667	0.2108	1.67	0.52

Table 2. Basic population genetic statistics for lineage 2. Ordered by increasing gene diversity.

Population	Sample size	Gene Diversity	Gene Diversity Standard Deviation	No Alleles	No Alleles SD
Menagerie	3	0.1111	0.1111	1.17	0.41
NorthFork	7	0.1270	0.0840	1.33	0.52
HoquiamWA	2	0.1667	0.1667	1.17	0.41
Salal	4	0.1944	0.1248	1.33	0.52
Lower	9	0.2269	0.0844	1.83	0.75
EdwardsOld	8	0.2917	0.1150	2.17	1.17
JunoHill	12	0.3586	0.1108	2.83	1.47
Upper	4	0.4167	0.1411	1.83	0.75
Phipps	7	0.4206	0.1130	2.33	1.03
BixbyOld	6	0.4222	0.1056	2.17	0.75
CoalCreek	8	0.4226	0.1563	2.67	1.51
GoldBeach	16	0.4458	0.1194	3.17	1.33
CoalOld	9	0.4676	0.1500	2.67	1.51
DriftCreek	8	0.4762	0.1267	2.83	1.33
PrairieOld	9	0.4769	0.0704	2.67	0.52
Acey	5	0.5333	0.1406	2.50	1.22
Limestone	3	0.6111	0.2003	2.17	0.98

locations where Douglas-fir was planted as an exotic. Populations in Italy, Switzerland, and France may have been founded by genotypes originating from Idaho. This agrees completely with what we know about the planting stock used to establish Douglas-fir plantations in Europe. Isolates from New Zealand's South Island appears most closely related to genotypes from the Cascade mountains in Oregon, while the North Island population is more closely related to isolates from western Washington.

Individual population statistics for lineage 2 are presented in Table 2. The average gene diversity across populations is lower for lineage 2 (0.36) than it is for lineage 1 (0.43). However, the range of values is also smaller for populations of lineage 2, with neither the extreme high nor low values exhibited by populations of lineage 1. One interpretation of this result could be that individuals of lineage 2 mate more randomly. The only two populations with gene diversity above 0.5 are the two healthiest sites in the sample (Figure 4). Below 0.4 are the moderately and severely diseased sites. This relatively low

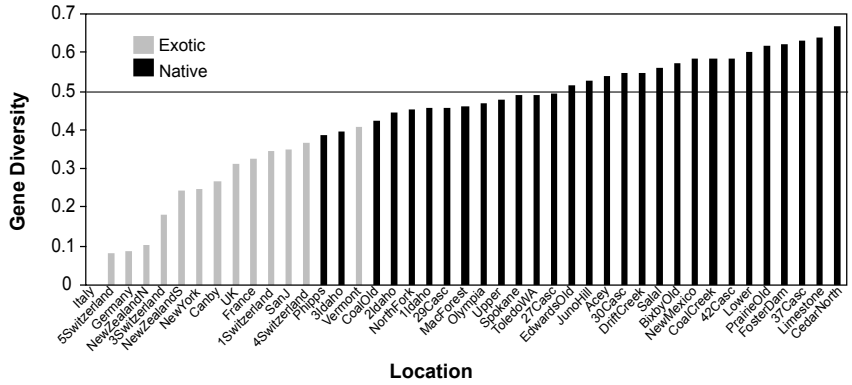

Figure 2. Microsatellite gene diversity for populations of lineage 1. Genetic diversity is generally lower in the locations where Douglas-fir has been planted as an exotic species.

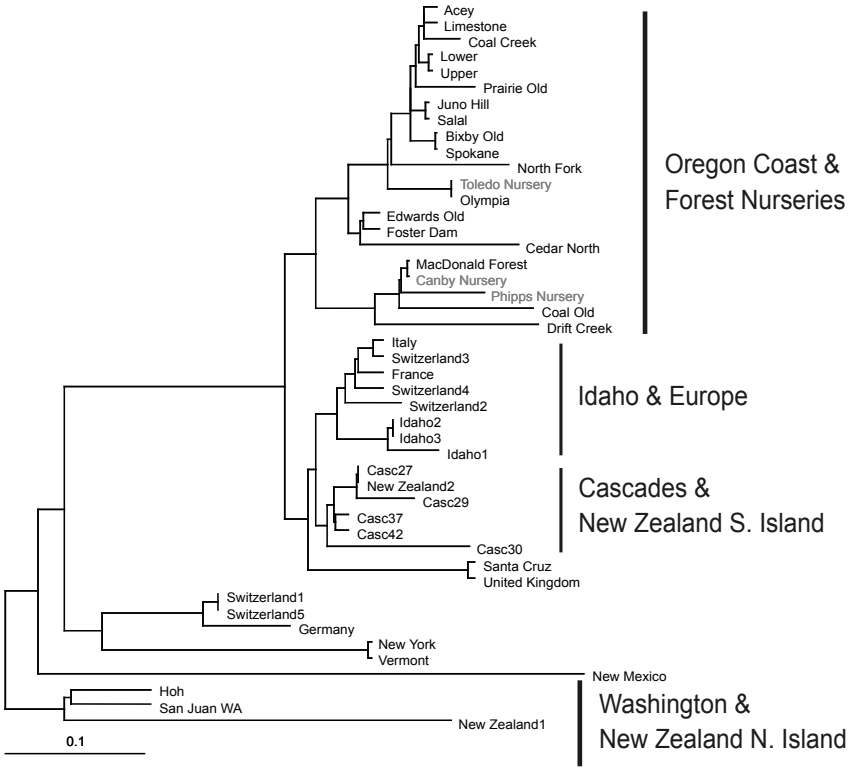

Figure 3. Genetic relationships among populations of P. gaeumannii lineage 1.

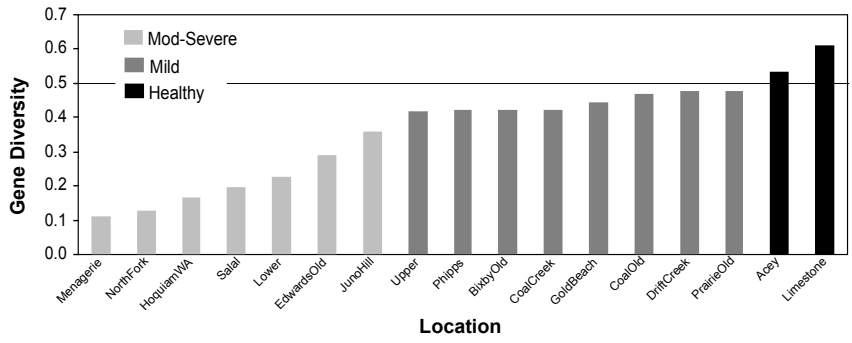

Figure 4. Microsatellite gene diversity for populations of lineage 2: More severely diseased sites have lower genetic diversity.

genetic diversity is suggestive of an epidemic-type population structure which is distinguished by the occurrence of one or a few highly successful genotypes.

Genetic relationships among populations of lineage 2 are depicted in Figure 5. Populations of this lineage generally segregate into two groups. One group consists almost entirely of Tillamook populations at the center of the current epidemic. A notable exception is the population surrounding the Oregon Dept. of Forestry's nursery. Genetically, this population is more similar to populations in the Tillamook area than to the nearby Gold Beach population. The other group consists of populations further to the south from the epidemic area.

Within Tillamook County, lineage 2 was correlated with disease (Figure 6). As the proportion of the Coastal lineage increased in stands, trees retained fewer needles. At our worst site, trees only had about 17% of their needles left and over 70% of the isolates obtained from that site were Coastal lineage.

In order to estimate reproductive mode in the epidemic area, we genotyped 33 isolates from a single 15 year old tree at the Juno Hill site. There were 29 different genotypes, most belonging to lineage 1. We found no evidence ($P=0.07$) that the multilocus index of association differed from that expected from a single recombining population of lineage 1. This suggests random mating within the tree canopy. However, at the stand level, there is evidence ($P<0.01$) of non-random reproduction at Juno Hill ($I_A=2.6$), Lower Stone ($I_A=1.9$), and Upper Stone ($I_A=1.6$). This

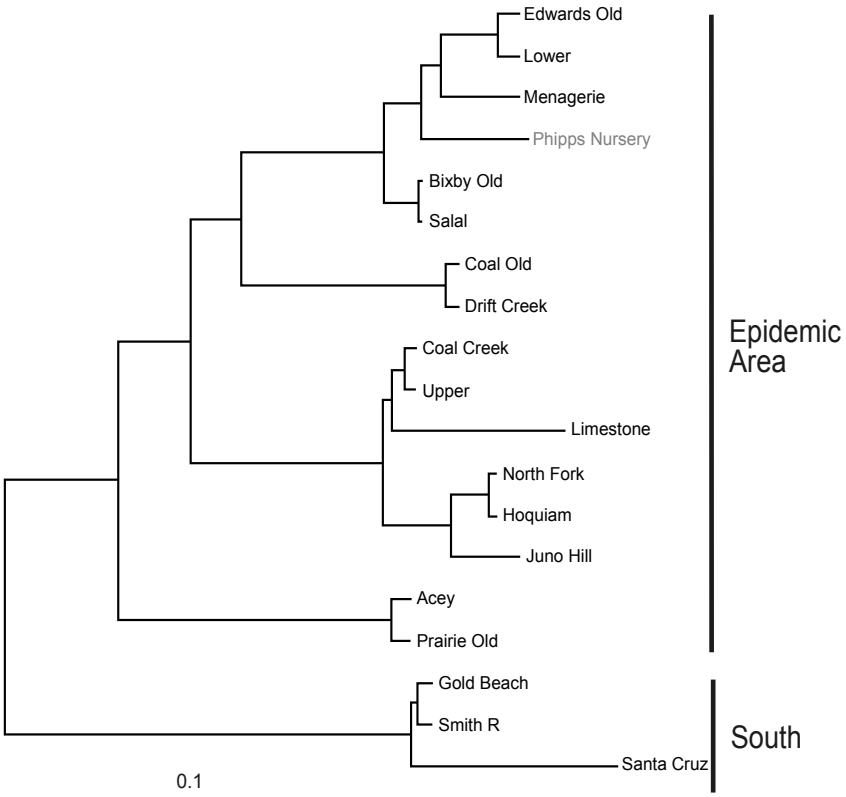

Figure 5. Genetic relationships among populations of P. gaeumannii lineage 2.

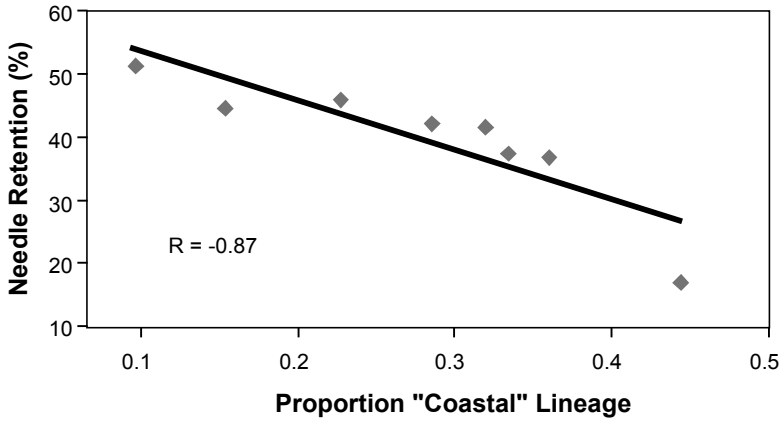

Figure 6. Microsatellite Data: Correlation between lineage 2 and needle retention at 8 sites.

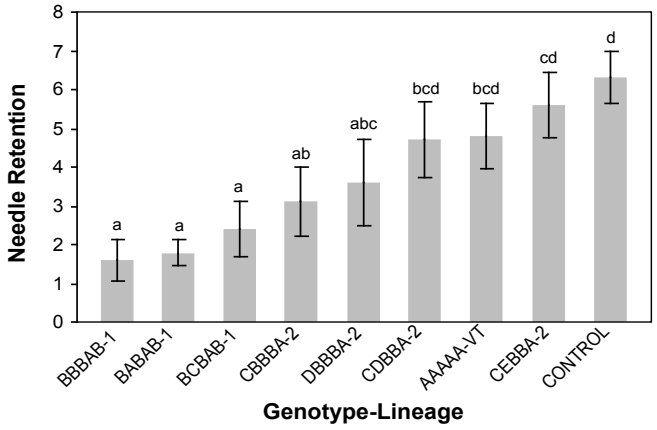

Figure 7. Mean needle retention ratings of seedlings inoculated with 8 P. gaeumannii genotypes in 2002. Bars marked by different letters are significantly different (p<0.05). Vertical lines indicate standard errors.

result is likely due to population admixture.

Differences in pathogenicity between lineages

Seedlings inoculated with different *P. gaeumannii* isolates showed a gradient of needle loss. Isolates of lineage 1 tended to cause less severe defoliation than did isolates of lineage 2 (Figure 7). When results for all genotypes were combined by lineage, i.e. all the trees inoculated with lineage 1 isolates compared with trees inoculated with lineage 2 isolates, the defoliation caused by lineage 1 was significantly greater than that caused by lineage 2 (Figure 8). This result agrees with similar inoculations performed in 1997 and 2001. However, because lineage 2, rather than lineage 1, was

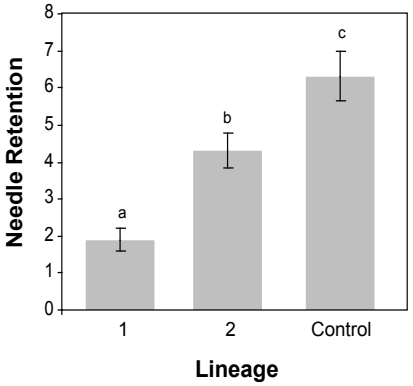

Figure 8. Comparison of seedling needle retention ratings where genotypes comprising the individual lineages are combined. Bars marked by different letters are significantly different (p<0.05). Vertical lines indicate standard errors.

positively correlated with disease in field plots, this suggests an interaction between genotype and environment may be influencing disease severity in the field. Possibly the more maritime influenced environment near Tillamook is more favorabe for growth or fecundity of predominantly coastal lineage 2, while lineage 1, the lineage more frequently found in the interior, is better adapted to the relatively drier conditions away from the coast. It is worth noting that 15 of 16 isolates collected from MacDonald Forest genotyped as lineage 1.

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Winton, L.M. 2001. Phylogenetics, Population Genetics, Molecular Epidemiology, and Pathogenicity of the Douglas-fir Swiss Needle Cast Pathogen *Phaeocryptopus gaeumannii*. Ph.D. Dissertation, Dept. of Botany and Plant Pathology, Oregon State University, Corvallis, OR. 112 p.

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Control of Swiss Needle Cast in Forest Plantations by Aerially Applied Elemental Sulfur Fungicide

Jeffrey Stone, OSU; Gary Chastagner, WSU; Alan Kanaskie, ODF

Abstract

A field study was established to evaluate the efficacy of aerially applied sulfur fungicide for control of Swiss needle cast in Douglas-fir forest plantations. Paired plots of five acres each were established at six sites in the Oregon Coast Range. Half of the study sites were 15-20 year old plantations that had been pre-commercially thinned, half were 20-25 years old and had been commercially thinned. One plot of each pair received sulfur fungicide treatment at the rate of 60 lb/acre, applied twice in a two-week interval in early June 2002. For current-year foliage sampled in fall, 2002, aerial application of elemental sulfur fungicide resulted in increases in percent sulfur and SO_4 sulfur content as well as increased P, Ca, Mg, Mn, Z, and B. Percent Fe was lower in sulfur treated foliage, percent N, K, C, and Cu were not different between sulfur treated and untreated foliage. Similar trends were observed for current-year and one-year-old foliage sampled in fall, 2003, however only percent S and SO_4 content were statistically significant. Infection of one-year-old foliage sampled in 2002 and 2003 foliage was reduced significantly for both years in all plot pairs. During 2002, an additional trial was established in Washington to determine the effectiveness of a single application of several other types of fungicides in protecting needles from SNC. Materials in this trial, included Thiolux, several copper fungicides, a biologically-based material, and Daconil WeatherStik. Kocide and Daconil were the only materials that reduced SNC infection levels.

Introduction

There are few management options for controlling Swiss needle cast (SNC) in Douglas-fir forest plantations at present. Fungicidal control of SNC in forest plantations has met with mixed success where it has been attempted. 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, handspraying the same material at the same concentration reduced incidence of infection to below 42% compared to 100% in unsprayed control (Hood and van der Pas 1979). The disease is

effectively controlled in Christmas tree plantations by the fungicide chlorothalonil (Chastagner and Byther 1982, Skilling 1981, Hadfield and Douglas 1982). Annual applications of chlorothalonil are recommended beginning three years prior to planned harvest for marketable Christmas trees (Chastagner and Byther 1982). However, because of the longer duration of protection needed for Douglas-fir timber rotations, aerial fungicide sprays have not been considered an economically effective option for control of SNC in forest plantations. Furthermore, toxicity of chlorothalonil to fish and other aquatic organisms and its moderately long persistence in soil make it an unsuitable material for forest use.

Previous studies (Chastagner 2002, Chastagner and Stone 2001, Crane et al 2001, Stone et al 2000) have indicated that elemental sulfur formulations (Thiolux, Golden Dew) are moderately effective protectant fungicides for control of SNC. Although elemental sulfur fungicide has not been as effective as chlorothalonil in reducing infection by *Phaeocryptopus gaeumannii* in field studies (Chastagner and Stone 2001, Stone et al 2000), it has nevertheless shown moderate efficacy in reducing infection. Furthermore, elemental sulfur is classified as an EPA toxicity category IV material, the least toxic category. Sulfur is considered a very low toxicity material that poses a very low risk to human and animal health. Sulfur also has a very low toxicity to birds, fish and aquatic invertebrates and so its use in forestry applications is not subject to the same level of environmental concern as for chlorothalonil and other fungicides. Some field observations have also suggested that in addition to its fungicidal properties, elemental sulfur can act as a nutrient in sulfur-deficient soils, resulting in improved foliage color and increased growth.

The infection biology of *P. gauemannii* suggests that effective fungicidal control of SNC in forest plantations should require treatment for three or more consecutive years. Previous studies have shown that nearly all infection occurs only in newly expanding shoots. Needles that are not infected during the first growing season are much less likely to become infected during subsequent years (Capitano 1999, Hood and Kershaw 1975, Stone et al. 2000). Ascospores are released between April and July, with the maximum ascospore release occurring between mid-May through mid June (Michaels and Chastagner 1984, Stone et al. 2000). Because only newly expanding needles are the primary infection court, and because the period of maximum ascospore release is relatively brief, protectant fungicides applied to the susceptible foliage at bud break should result in long term reduction of infection in the treated foliage. If fungicide application is repeated for several consecutive years so that all needle cohorts attached on branches have received treatment, an overall reduction in infection and inoculum production in treated stands should result, reducing the need for further fungicide treatment to maintain SNC control.

Evaluations of elemental sulfur fungicides for control of SNC have to date been conducted as simulated aerial applications on individual small trees. Because of the interest of forest managers in the potential for use of elemental sulfur for control of SNC in operational stands, a study was established to evaluate aerially applied sulfur on 15 to 25-year old Douglas-fir stands in the Coast Range. The study sites represent a range of disease severity from moderate to severe. The objectives of this study are to evaluate efficacy of aerial application of elemental sulfur for control of SNC in operational forest plantations, identify problems in operational use, evaluate optimum age during rotation for treatment, evaluate growth responses, and determine whether disease severity affects response to treatment.

Materials and methods

Study sites

Four groups of study sites were established in spring of 2002 with the cooperation of The Simpson Timber Company, Starker Forests, Rayonier Inc., and the Oregon Department of Forestry. Each group consisted of a plot pair established in a 10 – 15-year old plantation and a plot pair in a 20–25-year-old plantation, except the Rayonier site which had two plot pairs in a 10-15-year old plantation. Each plot pair consisted of two five-acre plots within the same stand (15 acre minimum) with a uniform topography. One five-acre plot of each pair received the aerial sulfur application, the other was an untreated check. Additional criteria for the stands were that they should be primarily stocked with Douglas-fir, the 10 – 15-year-

old stands to have been precommercially thinned with a stocking of 300- 350 trees per acre, the 20 – 25-year-old stand to have been thinned within 3 years and have a stocking density of 200- 250 tpa. One-half acre permanent study plots were established in the center of each five-acre plot and all trees numbered and measured.

Sulfur fungicide application

Thiolux micronized elemental sulfur was applied to each treated plot by helicopter in early June, 2002 and again in June, 2003 at the rate of 60 lb/A, as two passes of 30 gal/ac applied in two perpendicular directions. At 10 to 14 days after the first application, a second application was made at the same rate. Each five-acre treatment plot received a total of 120 lb of Thiolux/A. The first treatment was applied when at least 50% of new shoots were 1 – 3″ expanded.

Foliage collection

In Oregon, foliage was collected manually by climbing ten randomly selected trees from each half-acre study plot. Two branches from the fifth whorl from the treetop were collected, and 3 – 4 tertiary lateral shoots were clipped and placed in collecting bags. At the Washington site, the tertiary lateral shoot samples were obtained from a single branch that was collected from 15 randomly selected trees in each plot. A collection of foliage was taken in fall 2002 after the first sulfur application for comparison of foliage elemental analysis. A second collection was taken in June 2003 for assessment of *P. gaeumannii* infection.

Analyses

For foliar nutrient analysis, foliage samples were collected in fall 2002 and 2003, separated into age classes, placed in paper bags labeled by site/treatment/tree/foliage age, and air dried. Elemental analysis was performed by the Central analytical Laboratory of Oregon State University. For assessment of infection by *P. gaeumannii*, foliage samples were collected in late May in 2003 and 2004. For the Oregon sites, needles were separated by age class, the needles for each age class pooled for each tree, and a sample of 50 needles randomly drawn for each tree/age class. The 50 needles were affixed to 3 x 5″ index cards with double-sided adhesive tape and examined under the dissecting microscope at 40x for presence of pseudothecia of *P. gaeumannii*. Incidence was scored as the proportion of needles bearing *P. gaeumannii* pseudothecia. Severity, the proportion of stomata occupied by *P. gaeumannii* pseudothecia, was determined from the first 10 needles bearing pseudothecia. The needles were examined under a dissecting microscope fitted with a counting grid and the proportion of stomata occupied by pseudothecia in three segments (petiole, middle, tip) of each of the ten needles was determined. Infection index (NFX), the product of incidence times severity, was used as a response variable for comparisons of treatments. Statistical analyses were carried out with the Statgraphics statistical package (Manuguistics Inc, Rockville, MD).

For the Washington site, infection assessments were done by visually examining needles on the different age classes of shoots using a dissecting microscope. The incidence of infected needles was rated on a scale of 0 to 10, where 0 = no pseudothecia evident on any needles, 1 = 1-10% of the needles with pseudothecia, … 10 = 91-100% of the needles with one or more pseudothecia. The severity of infection was rated on a 0 to 6 scale, where 0 = no pseudothecia present, 1 < 1%, 2 = 1-10%, 3 = 11-25%, 4 = 26-50%, 5 = 51-75%, and 6 = >75% of the stomata occupied by pseudothecia. Again, an infection index, based on the product of the incidence and severity ratings, was used to statistically compare treatments using SAS Proprietary Software Release 8.1 (SAS Institute Inc, Cary, NC).

2002 Fungicide screening trial (DF 102)

In addition to the aerial sulfur fungicide studies, a trial was also established in Washington to examine the effectiveness of several other types of fungicides in protecting needles from SNC (Table 3). Materials included in this trial are Daconil WeatherStik, Thiolux, several copper fungicides (Kocide DF, Kop-R-spray, and Phyton 27) and a biologically-based material (QRD 131). A single application of each material was applied to one tree in each of 10 blocks on May 31, 2002. All treatments were applied with a Solo backpack sprayer equipped with an 8003 nozzle @ 15 psi. Trees were sprayed to wet and the length of new growth

ranged from 1.5 to 3.5 inches at the time of application. A non-sprayed tree in each block served as checks.

The effects of these treatments on disease development were assessed by harvesting a single branch from the middle portion of each tree on March 10, 2003. Infection levels were assessed as described for the Washington aerial Thiolux study. In addition, needle loss and color were also rated. Needle loss was rated on a scale of 0 to 10, where 0 = none, 1 = 1-10%, 2 = 11-20%, 3 = 21-30%,…, and 10 = 91-100% loss. Needle color was rated on a 1 to 6 scale, where 1 = healthy-appearing dark green needles, 2 = healthy-appearing green needles, 3 = needles with a slight yellow mottling on a green background that may also have brown spots or tips on the needles, 4 = dull green needles with moderate chlorosis that may also have brown spots or tips on the needles, 5 = extensive yellowing/browning, and 6 = uniformly yellow needles that may have some brown spots or tips.

Results

Nutrient analysis

Current-year foliage collected at both the Oregon and Washington sites five to six months following aerial sulfur applications in 2002 and 2003 had greater percentages of sulfur and greater amounts of sulfate-sulfur than the unsprayed foliage, as would be expected. The sulfate-sulfur content of treated needles was more than two times that of the unsprayed needles in current-year foliage sampled in fall 2002, and was approximately three times greater in the same foliage one year later and in the current year foliage sampled in fall, 2003. Percent phosphorus, calcium, magnesium, manganese, zinc and boron were also higher in the sulfur treated foliage sampled in 2002. A similar trend was observed for the 2002 and 2003 foliage sampled in 2003, but the differences were not statistically significant. Percent nitrogen, potassium, copper and carbon were not different between the sprayed and unsprayed foliage for either year sampled (Tables 2, 3).

Phaeocryptopus gaeumannii infection

Aerially applied sulfur fungicide significantly reduced infection in one-year-old needles by *P. gaeumannii* in all Oregon plots in both 2002 and 2003 (Table 4, Figures 1, 2). Differences in infection levels were significantly lower for the sulfur treated foli-

Table 1. Products included in 2002 Washington fungicide trials.

Trade name and formulation	Active ingredient
Daconil WeatherStik 720	chlorothalonil
Golden Dew Sulfur 92%	sulfur
Kocide DF	copper hydroxide, copper metallic equivalent 40%
Kop-R-Spray	copper ammonium carbonate, copper metallic equivalent 8%
Phyton 27	copper sulphate pentahydrate, copper metallic equivalent 5.5%
QRD 131 AS	*Bacillus* spp.
Tactic sticker	synthetic latex and organosilicone
Thiolux 80W	sulfur

Table 2. Effect of sulfur application on foliage nutrient levels. 2002 foliage sprayed in June, 2002, collected and analyzed Nov, Dec 2002. Summary of all study sites (Oregon: ODF, Starker, Simpson. Washington: WSU/Rayonier). Two-factor ANOVA. Bold indicates significant a $p < 0.05$.

	Sulfur Treatment				
2002 Foliage	Spray		No Spray		
Response	mean	SD	mean	SD	p
S percent	**0.044**	**0.015**	**0.026**	**0.008**	**0.0000**
SO_4-S ppm	**240.07**	**160.51**	**100.94**	**86.20**	**0.0000**
N percent	1.71	0.248	1.65	0.196	0.0483
P percent	**0.169**	**0.053**	**0.146**	**0.041**	**0.0000**
K percent	0.780	0.159	0.772	0.169	0.7605
Ca percent	**0.278**	**0.082**	**0.219**	**0.051**	**0.0000**
Mg percent	**0.126**	**0.041**	**0.110**	**0.030**	**0.0005**
Fe ppm	**50.50**	**17.15**	**53.70**	**11.60**	**0.0309**
Mn ppm	**117.71**	**26.68**	**106.63**	**33.04**	**0.0024**
Zn ppm	**13.21**	**4.69**	**11.27**	**4.24**	**0.0005**
B ppm	**21.53**	**7.38**	**18.95**	**6.02**	**0.0058**
Cu ppm	4.76	1.06	4.45	0.93	0.0627
C percent	53.05	1.39	52.99	1.39	0.7516

Table 3. Effect of sulfur application on foliage nutrient levels. Foliage sprayed in June, 2002, and June, 2003. Foliage from the 2002 and 2003 internodes was collected and analyzed Nov, Dec 2003. Summary of all study sites (Oregon: ODF, Starker, Simpson. Washington: WSU/Rayonier). Two-factor ANOVA. Bold indicates significant a $p < 0.05$.

2002 Foliage	Sulfur Treatment				
	Spray		No Spray		
Response	mean	SD	mean	SD	p
S percent	**0.20**	**0.02**	**0.13**	**0.01**	**0.000**
SO_4-S ppm	**326.82**	**84.67**	**98.61**	**94.27**	**0.001**
N percent	1.68	0.07	1.62	0.24	0.514
P percent	0.17	0.04	0.14	0.03	0.235
K percent	0.75	0.21	0.71	0.14	0.730
Ca percent	0.38	0.08	0.35	0.09	0.503
Mg percent	0.12	0.01	0.10	0.02	0.014
Fe ppm	58.34	23.10	52.28	14.10	0.595
Mn ppm	120.25	30.01	114.01	30.94	0.730
Zn ppm	9.75	2.33	9.70	2.13	0.967
B ppm	20.37	4.96	18.29	5.34	0.499
Cu ppm	3.45	0.52	3.16	0.61	0.391
C percent	51.97	0.57	52.24	0.44	
2003 Foliage	Sulfur Treatment				
	Spray		No Spray		
Response	mean	SD	mean	SD	p
S percent	**0.19**	**0.03**	**0.11**	**0.01**	**0.000**
SO_4-S ppm	**271.77**	**116.48**	**92.16**	**90.06**	**0.013**
N percent	1.66	0.10	1.69	0.20	0.734
P percent	0.17	0.03	0.16	0.03	0.443
K percent	0.69	0.17	0.74	0.10	0.604
Ca percent	0.34	0.09	0.28	0.04	0.134
Mg percent	0.14	0.03	0.12	0.01	0.134
Fe ppm	53.53	22.24	47.02	9.39	0.524
Mn ppm	108.67	33.55	91.71	12.41	0.273
Zn ppm	11.11	2.70	11.84	2.38	0.631
B ppm	19.84	3.38	20.69	3.54	0.681
Cu ppm	3.65	0.36	3.76	0.46	0.678
C percent	51.90	0.68	51.80	0.38	

Table 4. Comparison of *P. gaeumannii* infection index (incidence x severity) in sulfur sprayed vs. unsprayed one-year-old foliage (2002 foliage collected June 2003 and 2003 foliage collected June 2004) at Oregon sites. Significance levels are for a two-sample t-test comaprison of NFX means (sulfur vs. check) for 2002 foliage.

Site				
2002 Foliage	**Sulfur**	**Check**	**Difference**	**p**
Starker 10-yr-old	0.003	0.0696	0.067	0.001
Starker 20-yr-old	0.001	0.1216	0.121	0.001
Simpson 10-yr-old	0.073	0.1766	0.103	0.009
Simpson 25-yr-old	0.029	0.1067	0.078	0.023
ODF W Oregon 18 yr old	0.001	0.0479	0.047	0.001
ODF Tillamook	0.011	0.1128	0.102	0.001
2003 Foliage				
Starker 10-yr-old	0	0.002	0.002	0.007
Starker 20-yr-old	0	0.021	0.021	0.180
Simpson 10-yr-old	0.01	0.133	0.123	0.004
Simpson 25-yr-old	0	0.070	0.070	0.025
ODF W Oregon 18-yr-old	0	0.007	0.007	0.002
ODF Tillamook 25-yr-old	0.002	0.018	0.016	0.010

age for all plot pairs except the Starker 20 year old site in 2004. Infection levels in foliage from the untreated check were low at this site compared to the previous year (Table 4, Figure 2). For the 2002 foliage, the magnitude of the differences in overall infection index varied from about 0.05 for the ODF No Womans Land site to more than 0.1 for the two Starker Forests plot pairs. For 2003 foliage differences were somewhat smaller, 0.002-0.123 (Table 4). Incidence of infection, the proportion of needles bearing at least one pseudothecium, was reduced for all treated plots except the Simpson Timber Co. 10-year-old plot pair in 2003. For the 2003 foliage, comparison of incidence of infection across all sites by ANOVA showed a significant reduction in infection for the sulfur treatment ($p<0.002$, data not shown).

Sulfur application also significantly reduced *P. gaeumannii* infection at the Washington sites. Disease ratings for one- and two-year-old foliage were analyzed for the Washington site in 2003. As expected, there was no difference between sprayed and unsprayed foliage for the 2001 foliage sampled in spring 2003. For the 2002 and 2003 foliage, however, infection by *P. gaeumannii* was significantly reduced (Table 5). Incidence of infection in the 2002 foliage sampled in 2003 was reduced (0.7 vs. 8.8). For the same needle cohort sampled in 2004, incidence of infection was 2.9 in the treated, 10 (100%) in the untreated. For 2003 needles sampled in 2004, incidence of infection was 0.3 for sprayed trees and 4.9 for unsprayed (data not shown).

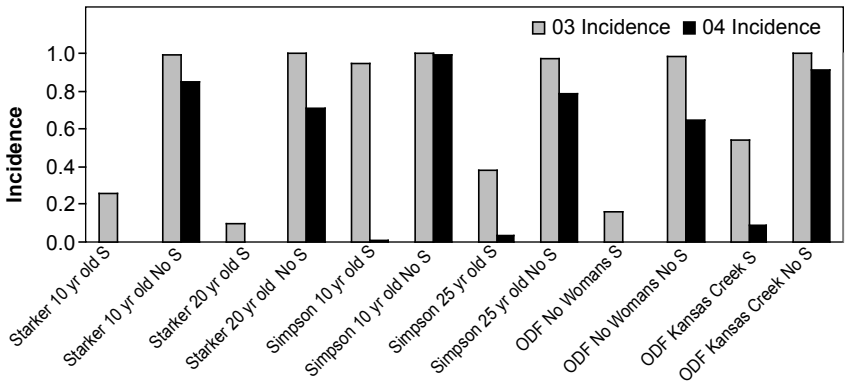

Figure 1. Comparison of incidence of infection in one-year-old foliage from sulfur sprayed and unsprayed stands in the Oregon Coast Range.

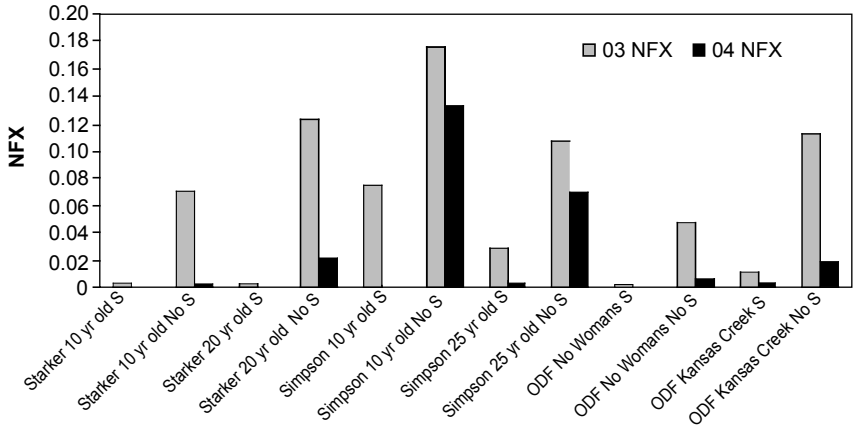

Figure 2. Comparison of infection index (NFX) for one-year-old foliage from sulfur sprayed and unsprayed stands in the Oregon Coast Range.

2002 Fungicide screening trial (DF 102)

Only two of the treatments (Kocide @ 2lb and Daconil WeatherStik) significantly reduced the overall level of disease compared to the unsprayed check (Table 2). These were also the only two treatments that significantly reduced the incidence of needles with pseudothecia (Data not shown). Only a limited amount of needle loss was evident on the samples and there were no differences between treatments. Although most treatments had no effect on needle color, needles on trees sprayed with Kop-R-Spray had significantly poorer color than the needles on the unsprayed checks (Table 5).

Data from this trial confirms the effectiveness of a single ground based application of Daconil in controlling SNC, particularly under relatively low disease pressure. Of the other materials tested,

Table 5. Comparison of disease ratings in sulfur sprayed vs unsprayed one-year-old and two-year-old foliage collected in June 2003 and June 2004 from the Washington site. Age class 2001 needles were one year old when the sulfur sprays were applied in June 2002.

Disease Index	Sprayed	Check	P value (t-test)
2003 Sample			
2001 needles	34.8	36.4	0.886
2002 needles	0.7	13.1	0.001
2004 Sample			
2001 needles	38.1	40	ns
2002 needles	5.4	28.9	sd
2003 needles	0.3	5.6	sd

Table 6. Effect of a single application of fungicide in 2002 on the development of Swiss needle cast in 2003.

Treatment[1]	Product per 100 gallons	Disease index[2]	Needle loss[2]	Needle color[2]
QRD 131 AS	3 gal	14.0 a	0.1 a	2.4 ab
Check	-	13.0 ab	0.1 a	1.7 bc
Phyton 27	25 oz	11.7 abc	0.1 a	2.6 ab
Kop-R-Spray	2 qts	9.5 abc	0.0 a	2.8 a
Thiolux 80W	60 lbs	9.2 abc	0.2 a	2.0 abc
Kocide DF	4 lbs	8.3 abc	0.0 a	2.3 abc
Thiolux 80W	90 lbs	7.2 bc	0.0 a	1.6 bc
Kocide DF	2 lbs	5.7 cd	0.0 a	2.0 abc
Daconil WeatherStik 720	5.5 pts	0.2 d	0.0 a	1.3 c

[1] Each treatment was applied to a single randomly selected tree in each of 10 blocks on May 31. 2002 and the foliage was sprayed to wet.

[2] Disease index and needle color/loss data are for samples collected on March 10, 2003. Numbers in columns followed by the same letter are not significantly different, P=0.05, DMRT.

Kocide appears to be an additional fungicide that may have the potential to control SNC. However, additional studies are needed to obtain a better understanding of optimal rates and the effect of multiple applications of this material on disease development.

Discussion

Elemental sulfur is one of the oldest known pesticides. Its use to control plant diseases dates from at least 1800, although its pesticide properties were known as early as 1000 B.C. (Tweedy 1969). Sulfur is currently registered by the U.S. Environmental Protection Agency for use as an insecticide, fungicide, and rodenticide on several hundred food and feed crop, ornamental, turf and residential uses. It is also used as a fertilizer or soil amendment. Sulfur is applied in dust, granular or liquid form, and is an active ingredient in numerous registered pesticide products (Thomson 1993). Although it has long been used for control of fungal diseases, its mode of action against fungal cells is not fully understood. It is generally thought that sulfur interferes with oxidative phosphorylation (respiration) by acting as an electron acceptor from cytochromeB, thus interrupting the mitochondrial electron transport chain (Tweedy (1969). It is generally used as a protectant or contact fungicide, i.e. it has no systemic or eradicant activity. Elemental sulfur has recently been reported to be produced by some plants as defense responses to infection by pathogenic fungi (Williams and Cooper 2004). Elemental sulfur was inhibitory to *P. gaeumannii* ascospore germination and germ hypha growth at relatively high concentrations (Stone et al 2000).

Aerially applied elemental sulfur significantly reduced P. gaeumannii infection in treated foliage in both 2002 and 2003. Overall infection levels in the study sites were somewhat lower in 2003, even in the untreated plots. Infection levels were much lower in the treated plots in 2003, probably reflecting reduced inoculum levels from the treatment of the previous year. Sites that had relatively high infection levels in 2003, such as the ODF Kansas Creek and Simpson 10-yr-old stand had very low infection levels in the sulfur treated plots in 2004.

Results of this study suggest that aerially applied elemental sulfur could be effective in reducing foliage infection by *P. gaeumanii* in forest plantations, and may be a useful tool for SNC management. In addition to its effect in reducing foliage infection by *P. gaeumannii*, elemental sulfur also increased foliage content of several elements, suggesting that it is also acting as a nutritional supplement. As expected, foliar content of SO_4 sulfur was higher in the treated plots, but higher levels of P, Ca, Mg, Mn, and B in the treated foliage in 2003 suggest that uptake of these elements may have been increased by sulfur applications.

Whether of not elemental sulfur will be of operation use will require further investigation and longer term study. The prohibitive expense of fungicide application has generally precluded their use for control of foliage diseases in forest plantations. A cost benefit model taking into account plantation age, growth differential, fungicide application costs etc would be helpful to managers considering whether or not to invest in chemical control of SNC. A further consideration is that residual effects of fungicide treatment appear to be relatively short term. *Phaeocryptopus* infection levels were significantly reduced, and needle retention increased after five consecutive years of chlorothalonil fungicide spray in a coastal Douglas-fir plantation. However, infection levels quickly returned to pretreatment levels after cessation of spray treatments, and infection levels between fungicide treated and untreated plots were not significantly different two years after the final fungicide applications (Stone et al, 2003). This suggests that fungicidal control of SNC can only be accomplished by continued fungicide application throughout a rotation. Unless increases in growth following control of SNC persist over a longer period of time, this suggests that the use of fungicides to control SNC will probably not be cost effective. Additional research is needed to determine the effects of sulfur fungicide sprays on growth and how long increases in growth rates persist following the cessation of applications.

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Growth Responses to Sulfur Application in Douglas-fir Stands with Swiss Needle Cast

Doug Maguire, OSU; Jeff Stone, OSU; Doug Mainwaring, OSU Mark Gourley, Starker Forests; Alan Kanaskie, ODF; and Charley Moyer, Green Diamond

Abstract

Sulfur applications were tested on five pairs of plots in Oregon, one plot of each pair serving as control and the other plot receiving aerial application of micronized sulfur. No treatment effects on either basal area growth or height growth could be detected by analysis of variance. Introduction of stand density and initial height as covariates did not help to detect sulfur treatment effects.

Introduction

Sulfur has shown to offer some potential for ameliorating Swiss needle cast after recent operational applications. An experiment was initiated in spring of 2002 to test the effect of aerial application of sulfur on Swiss needle cast symptoms, the abundance of the causal fungus, and the growth of Douglas-fir (see Stone et al. 2004; this SNCC Annual Report; Control of Swiss needle cast in forest plantations by aerially applied elemental sulfur fungicide). The objective of this report is to present the results for tree growth during the first two years of sulfur application (2002-2003).

Methods

Experimental units were 5-ac units selected as a pair, with one unit serving as control and the other treated by aerial application of micronized sulfur (Stone et al. 2004). Within each experimental unit, a 0.5-ac measure plot was established. All trees were tagged and measured for dbh (nearest 0.1 cm) before the growing season in 2002, and a subsample of at least Douglas-fir trees was measured for total height and height to crown base (nearest 0.1m). The experimental units were then treated aerially with micronized sulfur, twice during June in each of the two growing seasons. After the second growing season, the 0.5-ac plots were remeasured. Basal area growth and height growth were tested by analysis of variance and analysis of covariance. Five plot pairs established in the Coast Range of Oregon were available for analysis.

Results and Discussion

Analysis of variance showed no significant basal area or height growth response to the sulfur applications (Fig. 1). Three of the five installations analyzed showed positive basal area growth response to sulfur and two showed a negative response (Figs. 2-3). Height growth response was a bit more consistent, with positive response on 4 installations and negative response on another. Analysis of covariance with initial basal area and initial height as the covariates for basal area growth and height growth, respectively, produced similar results in that no treatment effects emerged. Because a relatively short period of time has elapsed since treatment, total foliage mass may have to continue to build back up for several more years until tree growth responds to the sulfur treatments.

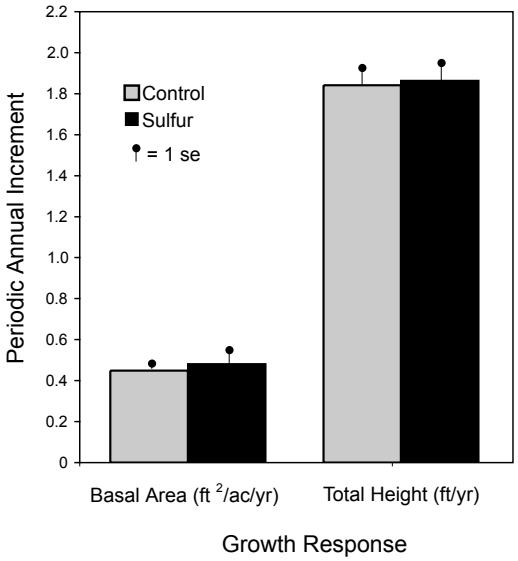

Figure 1. Mean basal area growth and height growth for the five Oregon sulfur sites.

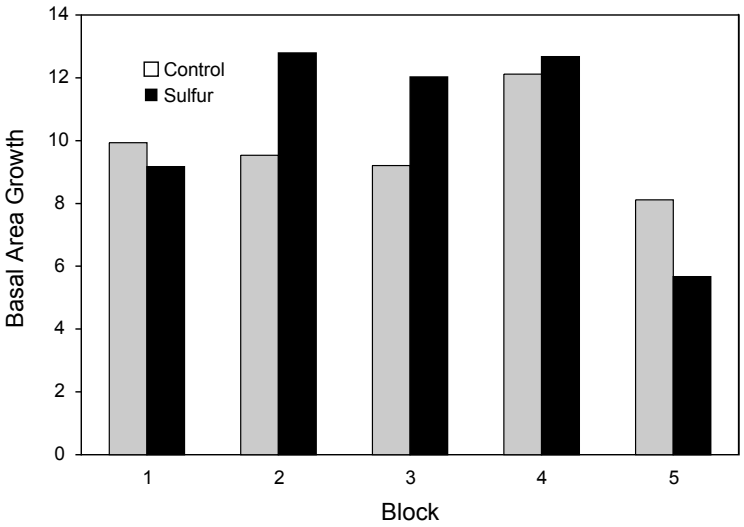

Figure 2. Basal area growth for treated and untreated plot at each installation.

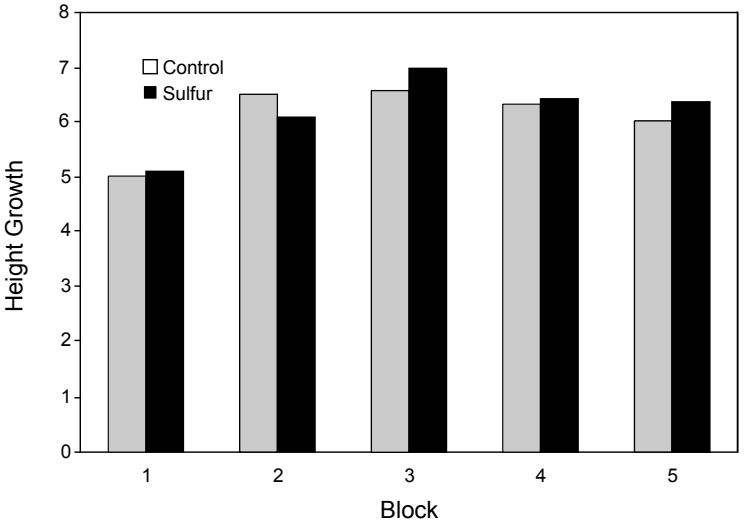

Figure 3. Height growth for treated and untreated plot at each installation.

Effects of Vegetation Management and Fertilization on Douglas-Fir Growth across a Gradient of Swiss Needle Cast

Robin Rose and Lee Rosner

Introduction

This study was designed to evaluate the potential to increase vigor and growth of Douglas-fir saplings in areas affected with Swiss needle cast (SNC) through vegetation management and/or fertilization. Severely infected Douglas-fir saplings typically cast off many of their second- and third-year needles, which increases penetration of sunlight to the forest floor. Increased light penetration can increase competing vegetation cover, which has the potential to further suppress growth. The role of site fertility, particularly nitrogen levels, in SNC pathology is poorly understood. This study was initiated to better understand the potential to enhance growth and/or reduce disease incidence in Douglas-fir saplings through vegetation management and fertilization.

Materials and Methods

This study was installed in 1999 on six-year-old Douglas-fir plantations at three different sites across an east/west transect of the Oregon Coast Range. The coastal site (South Drake) is located between Toledo and Siletz (Plum Creek Timber Co). The second site (Bushy Peterson) is midway between the coast and the Willamette Valley near Eddyville (Starker Forest Inc.). The third site (Summit) is on the western valley fringe near the town of Summit (Starker Forest Inc.).

Experimental Design and Treatments

At each site the study was installed as a randomized complete block design with four or five replicate blocks. The six treatments were structured as a 2 X 3 factorial with two levels of weed control and three levels of fertilization. Each treatment plot was 70 X 70 ft encompassing 25-35 operationally planted trees; the center-most 15 trees were evaluated.

The two vegetation control treatments were:

1) No control
2) Control of all competition for three consecutive years. Weeds were removed by slashing existing vegetation with chainsaws

followed by an application of sulfometuron and glyphosate in fall of 1998. Additional spring and fall applications of glyphosate were used to maintain vegetation-free conditions through spring 2002.

The three fertilization treatments were:

1) No Fertilization
2) Low N fertilization— In fall of 1999, and spring and fall of 2000, 400 grams of a controlled-release Simplot fertilizer (9-17-17) was applied to each tree. In spring and fall of 2001 the fertilizer rate was increased to 550 grams per tree and the fertilizer used changed to a soluble blend matching the formulations used previously. Over the three years of the study the approximate amount of fertilizer that has been applied is 3120 lbs/acre for a total N application of 280 lbs N/acre.
3) High N fertilization— In fall of 1999, and spring and fall of 2000, 400 grams of a controlled release Simplot fertilizer (18-17-17) was applied to each tree. In spring and fall of 2001 the fertilizer rate was increased to 550 grams per tree and the fertilizer used changed to a soluble blend matching the formulations use previously. Over the three years of the study the approximate amount of fertilizer that has been applied is 3120 lbs/acre for a total N application of 561 lbs N/acre.

Data Collection

Growth

Initial diameter at breast height (DBH) and height were measured in May 1999. Measurements were repeated in October 1999, 2000 and 2003.

Needle Retention

In April 2004 needle retention was evaluated across all study trees. Retention was evaluated on two well-exposed secondary lateral branches (defined as branches originating directly from a "side" branch, which is itself originating from the main trunk of the tree) approximately five whorls from the top of the tree.

For each branch, needle retention was estimated for each of the past four years of shoot growth (each of the four internodes produced between 2000 and 2003) as the percentage of needles remaining on the branch (relative to a typical recently flushed branch), according to the following "0 to 9" scale:

0 = 0 to 10 percent of needles present
1 = 11 to 20 percent of needles present
2 = 21 to 30 percent of needles present…
9 = 90 to 100 percent of needles present

For each tree the two sets of ratings from the two branches were averaged to create a single retention rating for each of the last four years of growth for each tree.

Pseudothecia Counts

Phaeocryptopus gaeumannii pseudothecia are being counted on needles of five randomly selected trees in each treatment plot at all three sites. Results of this analysis are not yet complete.

Foliar Nutrition Analysis

Although results of this analysis are not complete at the time of this report and are not presented, foliar nutrient analysis was conducted on "Vegetation Control/No fertilization" and "No Vegetation Control/ No Fertilization" treatment combinations at the South Drake site. For each treatment 3 trees in each of 3 blocks were randomly chosen for analysis. For each sample tree, branches were sampled at 3 heights in the tree and 3 age classes of needles were sampled from each height. This rigorous procedure should allow us to detect any changes in allocation of nutrients among the various age classes of needles as well as to evaluate variability in nutrient content as a result of sampling procedures.

Statistical Analysis

Analysis of covariance was used to detect differences in volume, DBH, and height growth due to fertilization and/or vegetation control treatments. The 1999 measurement of the same parameter was used as the covariate. Height: diameter ratio and the average of 3- and 4-year old needle retention ratings were analyzed using analysis of variance.

Results

Summary— Vegetation control increased volume growth at both the Bushy Petersen and South Drake sites and increased DBH

growth at all three sites. Fertilization increased volume growth at the South Drake site, but only when vegetation control was not applied. Vegetation control led to reductions in the height: diameter ratio all three sites.

Fertilization decreased needle retention in a rate-dependent fashion; increasing nitrogen additions from 0 lbs/acre to 280 lbs/acre to 561 lbs/acre reduced needle retention with each addition, for data averaged across all sites. Vegetation control reduced needle-retention only at the Summit site.

Tree Growth

Site Effects

Trees at Bushy Petersen have grown significantly faster than trees at South Drake or Summit. Mean individual tree volume measured in 2003 was 75.1 dm^3 at the Bushy Petersen site, 66.8 dm^3 at South Drake and 61.6 dm^3 at Summit.

Treatment Effects

Stem Volume

Vegetation control was the only factor significantly influencing volume growth at the Summit and Bushy Petersen sites, whereas both fertilization and vegetation control and the interaction of both factors significantly affected volume at South Drake (α=0.05). At Summit and Bushy Peterson vegetation control increased 2003 volume by 6.9% and 17.0% respectively (Table 1). At South Drake fertilization had no effect on volume when vegetation control was applied. In the absence of vegetation control, however,

Table 1. Main effect means and standard errors for volume, DBH, height and height: diameter ratios for trees measures in 2003 at Swiss Needle Cast Sites. Means within a parameter and treatment type labeled with the same letter are not significantly different (alpha=0.05).

		Fertilization			Weed Control		
Site	Parameter	Level	Mean	SE	Level	Mean	SE
Summit	Volume (dm3)	highN	61.6a	1.8	no	59.5b	1.6
		lowN	61.7a	1.8	yes	63.6a	1.6
		no	61.3a	1.8			
	DBH (cm)	highN	14.9a	0.3	no	14.4b	0.2
		lowN	14.9a	0.3	yes	15.3a	0.2
		no	14.7a	0.3			
	Height (cm)	highN	845.0a	6.9	no	856.8a	5.6
		lowN	837.9a	6.9	yes	832.2b	5.6
		no	850.5a	6.9			
	H:D	highN	57.4a	1.3	no	60.1a	1.2
		lowN	56.8a	1.3	yes	54.9b	1.2
		no	58.3a	1.3			
Bushy Peterson	Volume (dm3)	highN	74.8a	3.7	no	69.3b	3.5
		lowN	76.6a	3.7	yes	81.1a	3.5
		no	74.1a	3.7			
	DBH (cm)	highN	15.4a	0.4	no	14.7b	0.4
		lowN	15.7a	0.4	yes	16.2a	0.4
		no	15.3a	0.4			
	Height (cm)	highN	944.9a	10.5	no	941.4a	9.4
		lowN	943.0a	10.5	yes	947.1a	9.4
		no	944.8a	10.5			
	H:D	highN	62.4a	1.7	no	65.4a	1.6
		lowN	61.1a	1.7	yes	59.3b	1.6
		no	63.4a	1.7			
South Drake	DBH (cm)	highN	15.5a	0.2	no	15.0b	0.2
		lowN	16.0a	0.2	yes	16.3a	0.2
		no	15.4a	0.2			
	Height (cm)	highN	828.8a	8.4	no	832.4a	7.6
		lowN	843.2a	8.2	yes	841.6a	7.6
		no	838.9a	8.1			
	H:D	highN	54.0a	0.8	no	56.5a	0.7
		lowN	54.0a	0.8	yes	52.4b	0.7
		no	55.5a	0.8			

		Fert./ Weed Control Treatment Level	Mean	SE
	Volume (dm3)	Low N + Veg. Control	72.3a	2.4
		High N + Veg. Control	71.9a	2.4
		No Fert. + Veg. Control	71.7a	2.4
		Low N + No Veg. Control	67.5a	2.4
		No Fert. + No Veg. Control	59.9b	2.4
		High N + No Veg. Control	57.7b	2.4

the low nitrogen treatment improved growth to levels nearly equivalent to those attained through vegetation control.

DBH

Vegetation control significantly increased DBH growth at all three sites, while fertilization had no effect on DBH growth at any site (Table 1). The improvement in DBH due to vegetation control was 10.2%, 8.7% and 6.3% at the Bushy Petersen, South Drake and Summit sites, respectively.

Height

Vegetation control significantly reduced height growth by 2.9% at the Summit site (Table 1). This reduction in height growth at Summit accounts for the lack of a vegetation control effect on volume at this site, in light of the fact that vegetation control increased DBH growth.

Height: Diameter Ratio

Vegetation control reduced the height to diameter ratio at all three sites, while fertilization had no effect at any site (Table 1). As a result of vegetation control, the ratio fell from 65.4 to 59.3 at Bushy Petersen, from 56.5 to 52.4 at South Drake and from 60.1 to 54.9 at Summit.

Needle Retention

There were few obvious differences among sites or treatments in retention of one- and two-year-old needles (Table 2). Retention of both 3- and 4-year-old needles varied among sites as well as treatments. Whether analysis was carried out on retention of three-year-old needles, retention of 4-year-old needles or retention of both 3- and 4-year old needles (averaged), results did not differ significantly. Analysis of retention across both 3- and 4-year-old needles (averaged) is presented here.

Needle retention varied among the study sites. Needle retention was higher at Summit (3.97) and Bushy Peterson (3.93) than at South Drake (3.02). Retention was not significantly different between the Summit and Bushy Peterson sites.

Averaged across study sites, increasing rates of nitrogen fertilization decreased needle retention (Table 3). The pattern of reduced retention with increasing rate of N fertilization was statistically significant at the Bushy Peterson and South Drake sites. Fertilization did not significantly affect retention at the Summit site, although there was a non-significant trend of reduced retention with increased N fertilization.

On the other hand, there was no significant effect of vegetation control on needle retention averaged across sites as well as at Bushy Peterson or South Drake. At Summit vegetation control did affect needle retention, with weed control reducing average retention from 4.5 to 3.4 (Table 3).

Table 2. Main effect means and standard errors for retention of 1-4-year-old needles. Each annual needle compliment was rated on a scale of 0-9, 0=no needles retained, 9=all needles retained.

Effect	Level	Needle age	Mean Rating	Standard Error
Site	Summit	1-yr-old	8.97	0.02
		2-yr-old	8.47	0.08
		3-yr-old	6.08	0.20
		4-yr-old	1.78	0.19
	Bushy	1-yr-old	8.99	0.00
		2-yr-old	8.58	0.06
		3-yr-old	5.94	0.24
		4-yr-old	1.44	0.15
	Drake	1-yr-old	8.98	0.01
		2-yr-old	8.28	0.08
		3-yr-old	4.48	0.28
		4-yr-old	0.90	0.14
Fertilization	highN	1-yr-old	8.99	0.00
		2-yr-old	8.28	0.09
		3-yr-old	4.63	0.28
		4-yr-old	1.05	0.16
	lowN	1-yr-old	8.97	0.02
		2-yr-old	8.43	0.06
		3-yr-old	5.53	0.26
		4-yr-old	1.26	0.14
	none	1-yr-old	8.97	0.01
		2-yr-old	8.59	0.07
		3-yr-old	6.25	0.22
		4-yr-old	1.79	0.20
Weed Control	yes	1-yr-old	8.98	0.01
		2-yr-old	8.37	0.07
		3-yr-old	5.19	0.23
		4-yr-old	1.26	0.13
	no	1-yr-old	8.98	0.00
		2-yr-old	8.50	0.06
		3-yr-old	5.76	0.22
		4-yr-old	1.47	0.16

Table 3. Needles retention means and standard errors by site and treatment for each Swiss Needle Cast study site and pooled sites. Needle retention means represent an average of retention ratings for 3- and 4-year-old needles. Means within sites and treatments labeled with the same letter are not significantly different (alpha=0.05).

Site	Fertilization Level	Retention Mean (0-9)	Standard Error	Weed Control Level	Retention Mean (0-9)	Standard Error
Pooled sites	highN	3.07 c	0.22	no	3.79 a	0.19
	lowN	3.63 b	0.22	yes	3.44 a	0.19
	none	4.15 a	0.22			
Summit	highN	3.75 a	0.32	no	4.50 a	0.29
	lowN	3.90 a	0.32	yes	3.44 b	0.29
	none	4.26 a	0.32			
Bushy Peterson	highN	3.30 b	0.26	no	3.87 a	0.22
	lowN	4.17 a	0.26	yes	3.98 a	0.22
	none	4.31 a	0.26			
South Drake	highN	2.22 c	0.24	no	3.03 a	0.21
	lowN	2.92 b	0.24	yes	3.01 a	0.21
	none	3.93 a	0.24			

Discussion

The goal of this study was two-fold, 1) to evaluate the potential to increase vigor and growth of Douglas-fir saplings in areas affected with Swiss needle cast and 2) to evaluate the effect of fertilization and vegetation control on disease incidence. At this point some clear answers are emerging regarding the first objective, but we are still awaiting some analyses that may shine light on the second objective, which is clearly more difficult to evaluate.

Five years after the initiation of treatments, fertilization appears to have had no effect on volume growth, except at South Drake, where the lower rate of nitrogen increased growth, but only in the absence of vegetation control. Controlling competing vegetation, on the other hand, increased volume growth at all three sites. Vegetation control (averaged across fertilization treatments) increased 2003 volume by 6.9% at Summit and 17.0% at Bushy Peterson. Vegetation control (in the absence of fertilization) increased 2003 volume by 19.7% at South Drake.

Vegetation control reduced the height: diameter ratio at all three sites. Decreased height: diameter ratios have been associated with increased vigor in Douglas-fir (Cole and Newton, 1987), although the ratios in all of our treatments were much lower than those that have been associated with decreased height growth potential. Current size differences and possibly differences in growth form resulting from vegetation control treatments should lead to further separation of treatment means in future years.

Growth improvements resulting from vegetation control may be independent of Swiss Needle Cast occurrence in these plantations. Vegetation control in any six-year-old plantation with a significant presence of competing competition is likely to improve growth.

Given that needle retention in Douglas-fir has been associated with Swiss Needle Cast disease severity (Maguire et al. 2002), it seems fair to conclude that reduced needle retention at the South Drake site indicates the disease is most severe at that site. We are awaiting results of pseudothecia counts to confirm this observation. However, reduced retention due to increasing rates of nitrogen fertilization at two sites and vegetation control at one site does not necessarily indicate that these treatments had any effect on disease severity. The clear reduction in needle retention due to N fertilization rate may be a direct result of increased nutrient availability to pathogens established on needles, but results of pseudothecia evaluations are needed to provide evidence that supports or refutes this hypothesis. Alternatively, fertilization may have created foliar nutrient imbalances leading to poor needle retention independently of any pathogenic response.

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Growth and Mortality Models that Incorporate the Effects of Swiss Needle Cast; an Examination of SMC ORGANON Biases and Development of New Equations Using Data from the Growth Impact, Pre-commercial Thinning, and Commercial Thinning Studies

Aaron Weiskittel and Doug Maguire, OSU

Introduction

Validation is an important aspect of forest modeling, but it is often difficult to accomplish because of the lack of large, independent datasets. Validation becomes particularly important when the model is applied to novel situations for which it was not parameterized such as the Swiss needle cast (SNC) epidemic in the Oregon Coast Range. Swiss needle cast has a great potential to drastically increase growth model projection biases because it significantly modifies Douglas-fir crown structure and dynamics (Weiskittel 2003), which the commonly used ORGANON is quite sensitive to. This may require the development of new growth equations that incorporate the effects of SNC.

This study projected 5-yr growth for the growth impact study (GIS) plots and compared it to actual estimates from the inventory data. In addition, preliminary 5-yr diameter growth, height increment, and mortality equations as well as a static height to crown base model were developed, which all incorporate variables representing SNC severity.

Methods

Growth comparisons

The 75 plots that now comprise the SNCC GIS network were used in this simulation (Table 1) and the SMC variant of ORGANON was selected as the most appropriate model for this particular region. Since the plots are measured on a 2-yr cycle and ORGANON runs on a 5-yr cycle, tree dimensions in the fifth year were assumed to be the mean of the measurements taken in the fourth and sixth years of the study. Comparisons between actual and predicted values were made using a simultaneous F-test (Yang et

Table 1. Attributes of the 75 plots used in this analysis.

Variable	Mean	STD	Min	**Max**
DF 5-yr basal area growth	70.52	31.34	3.25	134.33
DF stems/ha	566.41	240.00	86.45	1482.00
DF basal area (m^2 ha^{-1})	25.96	9.52	2.19	48.32
DF QMD (cm)	24.80	6.27	7.26	37.69
Stand basal area (m^2 ha^{-1})	32.78	9.68	2.55	53.11
Average BH age (yr)	20.45	4.97	11.9	34.9
Average foliage retention (yr)	2.42	0.45	1.47	3.61
Average crown sparseness	6.19	2.19	3.14	14.38
Site index (Bruce 1981)	40.28	5.83	16.90	60.30
Top height (m)	17.29	4.03	4.85	29.65
Relative density (Curtis 1982)	6.80	1.88	0.92	10.46
Stand density index (Reineke 1933)	669.66	185.18	80.80	1031.22
Distance from coast (km)	15.26	7.31	0.96	31.87

al. 2004). This test is essentially designed to evaluate the regression $y_i = b_0 + b_1 \hat{y}_i$ by testing b_0=0 and b_1=1 simultaneously and is one of the most widely used tests for model validation. Comparisons were made at both the stand and individual tree levels. Mean plot biases were then regressed on several stand variables to determine influential factors.

Model development

Growth models presented in Hann et al. (2003) were initially fitted to the data and SNC variables such as crown sparseness index (CLSA) and foliage retention (FOLRET) were then included into the equation. The models were fitted using maximum likelihood with the inclusion of random effects and a first-order autoregressive error structure to account for the repeated and longitudinal nature of the dataset. Since Hann et al. (2003) did not detect an effect of a single thinning on mortality, all data, including the PCT and CT datasets, was used for this particular model (table 2).

For all other models, only the GIS, and PCT and CT control plots were used. Five-year height growth increment was modeled using the form presented in Hann and Ritchie (1986) as it had the lowest mean squared error (MSE) of several model forms for even-aged Douglas-fir (Hann and Ritchie 1988) and requires significantly fewer parameters than the model presented in Hann et al. (2003).

Table 2. Attributes of the modeling datasets (GIS=growth impact, PCT=pre-commercial thinning, and CT=commercial thinning) used in this analysis.

Variable	Mean	STD	Min	**Max**
Height to crown base (n=16193; GIS, PCT, CT)				
DBH (cm)	21.93	9.69	0.90	105.40
HT (m)	15.98	6.45	1.63	53.38
HCB (m)	4.99	4.67	0.00	35.55
CCFL (m^3 ha^{-1})	39.21	24.06	0.00	126.51
$CLSA_{TOP}$ (cm^2/cm)	7.12	1.40	1.90	10.39
BAPH (m^3 ha^{-1})	29.91	13.31	5.99	76.78
SI (m)	39.59	6.44	16.6	64.6
FOLRET (yrs.)	2.43	0.58	1.01	4.30
5-yr diameter growth (n=4898; GIS, PCT)				
DBH (cm)	17.14	6.91	0.90	55.00
HT (m)	11.93	4.33	1.43	31.28
CR	0.82	0.12	0.26	0.99
ΔDBH (cm)	4.11	2.41	1.5	18.85
CLSA (cm^2/cm)	6.79	2.24	0.18	27.19
BAL (m^3 ha^{-1})	11.26	8.16	0.00	50.26
SI (m)	43.53	6.96	13.40	64.60
BAPH (m^3 ha^{-1})	21.45	10.36	5.99	50.36
$CLSA_{TOP}$ (cm^2/cm)	5.08	1.83	2.24	10.92
5-yr height increment (n=3327; GIS, PCT)				
DBH (cm)	18.36	7.24	0.90	55.00
HT (cm)	12.47	4.38	1.63	31.28
CR	0.82	0.12	0.29	0.99
ΔHT (m)	3.86	1.19	1.01	9.55
CCFL (m^3 ha^{-1})				
CLSA (cm^2/cm)	6.54	2.38	0.18	27.19
SI (m)	43.55	7.02	13.40	64.60
FOLRET (yrs)	2.36	0.38	1.07	3.20
5-yr mortality rate (n=8732; GIS, PCT, CT)				
DBH (cm)	20.89	11.11	0.10	97.50
CR	0.72	0.26	0.29	0.99
CLSA (cm^2/cm)	6.99	2.68	1.01	90.69
BAL (m^3 ha^{-1})	13.19	13.46	0.00	75.12

Results

Stand

A significant difference between actual and predicted stand volume growth existed ($p<0.0001$; Figure 1).

ORGANON tended to overestimate stand volume growth by 29.7% (mean = -20.09 m^3 ha^{-1}, min = -81.57 m^3 $5ha^{-1}$, max = 27.28 m^3 ha^{-1}). The amount of bias tended to increase with stand quadratic mean diameter (QMD; $p=0.0014$) and foliage retention (FOLRET; $p=0.0133$), and decreased with site index (SI; $p=0.0003$) and stand mean breast height age (AGE_{BH}; $p=0.0009$). Compared to an average stand with low SNC (FOLRET=3.65), the mean bias in stand volume growth increased 100.4% for an average stand with high (FOLRET=1.65) SNC.

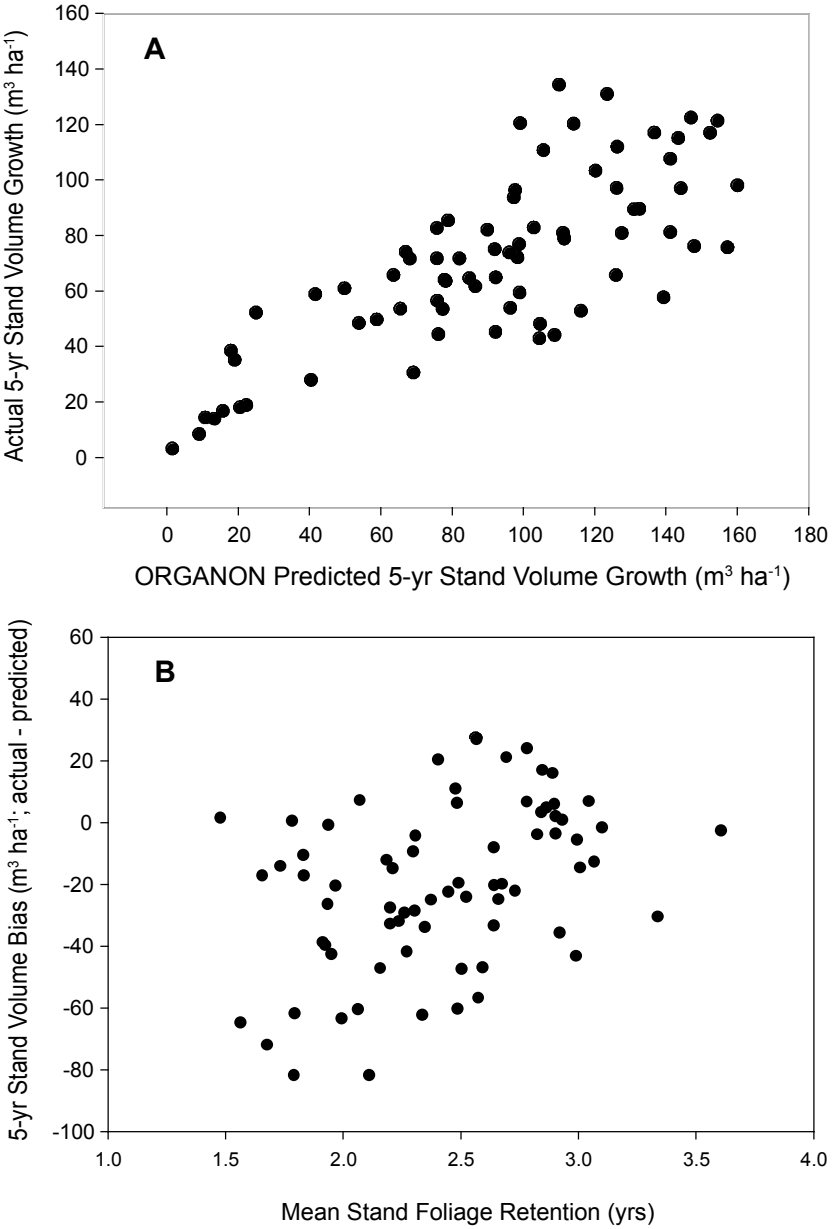

Figure 1. Biases in 5-yr stand volume growth. Graph A (top) is actual over ORGANON predicted 5-yr stand volume growth, while graph B (bottom) is bias (actual-predicted) over mean stand foliage retention.

Individual tree

A significant difference existed between actual and predicted 5-yr diameter growth ($p<0.0001$), height increment ($p<0.0001$), and crown recession ($p<0.0001$; Figure 2). Mean 5-yr bias was -0.90 ± 5.29 cm, -57.01 ± 438.39 cm, and -7.77 ± 287.75 cm for diameter growth, height increment, and crown recession, respectively. Mean stand diameter growth bias increased with QMD ($p=0.0081$) and FOLRET ($p=0.0046$), while it decreased with stand mean breast height age (AGE_{BH}; $p<0.0001$) and site index (SI; $p<0.0001$; Bruce 1981). Mean stand height increment bias increased with distance from the coast (COAST; $p=0.0102$) and FOLRET ($p=0.0229$). The bias decreased with QMD ($p=0.0479$), percent Douglas-fir basal area (PBA_{Df}; $p=0.0046$), and SI ($p=0.0030$). Bias in mean stand crown recession increased with the cosine transformation of slope and aspect (ASP1; (% slope)*cos ine(2π*(aspect/360)); $p=0.0042$), while it decreased with QMD ($p=0.0002$), PBA_{DF} ($p<0.0001$), percent western hemlock basal area (PBA_{WH}; $p=0.0007$), and the crown sparseness index (CLSA; $p=0.0033$) calculated using the sapwood taper equation presented in Weiskittel (2004). Compared to an average stand with low SNC (FOLRET=3.65, CLSA=6.12), mean bias increased 107.8, 88.0, and 87.7% for diameter growth, height increment, and crown recession, respectively, for an average stand with high (FOLRET=1.65, CLSA=5.42) SNC.

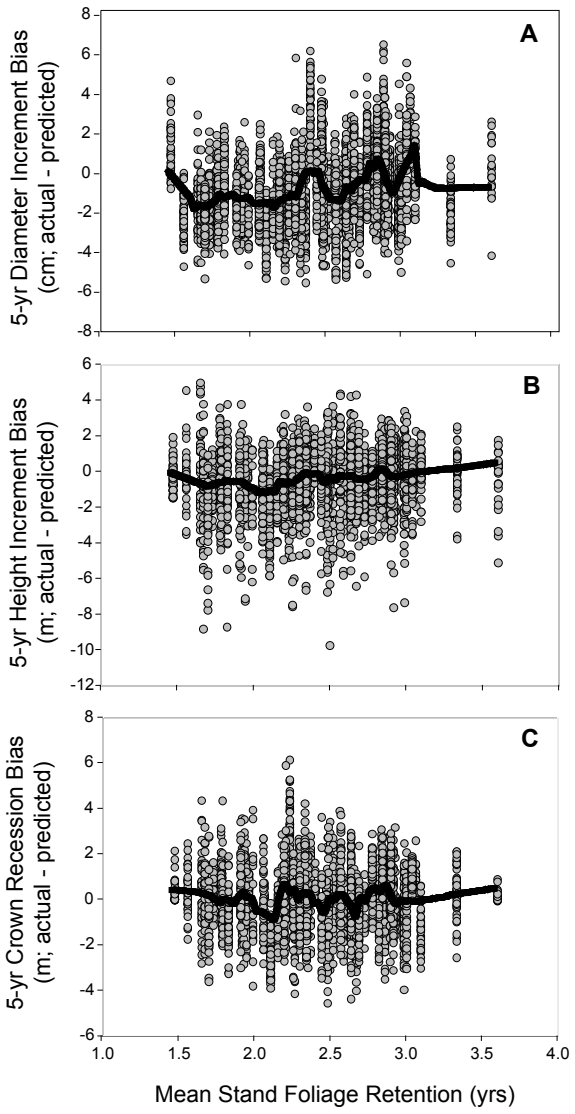

Figure 2. Biases occurred at the individual tree level. Graphs A (top), B (middle), and C (lower) are 5-yr diameter growth, height increment, and crown recesion biases, respectively, over mean stand foliage retention. The black solid lines are si=moothed trend lines fitted to the data.

SNC models

Height to crown base

Both plot mean FOLRET (p=0.0014) and CLSA (p<0.0001) showed a significant relationship with height to crown base after accounting for height (HT; p<0.0001), plot crown competition factor (CCFL; p<0.0001), plot basal area (BA; p<0.0001), the diameter to height ratio (DBH/HT; p<0.0001), SI (p<0.0001), and the interaction between SI and FOLRET (p=0.0006). Compared to an average-sized tree on a plot with low SNC, HCB is 6.9% higher for a similar sized tree on a plot with high SNC (Figure 3).

5-yr diameter increment

The alternative 5-yr diameter increment model presented in Hann et al. (2003, pg. 70) fit the data better than the original model presented in that analysis (AIC of 16812.51 vs. 16780.33). Plot mean FOLRET in 1998 did not show a significant relationship with 5-yr diameter increment (p=0.3807), while CLSA and plot mean CLSA in 1998 showed a significant relationship (p=0.0428 and p=0.0004, respectively). A likelihood ratio test indicated that a model including both tree-level CLSA and plot mean CLSA was superior (p=0.0006) to a model containing only one of these variables. Compared to an average-sized tree on a plot with low SNC, 5-yr diameter growth was reduced by 17.9% for a similar sized tree on a plot with high SNC (Figure 4).

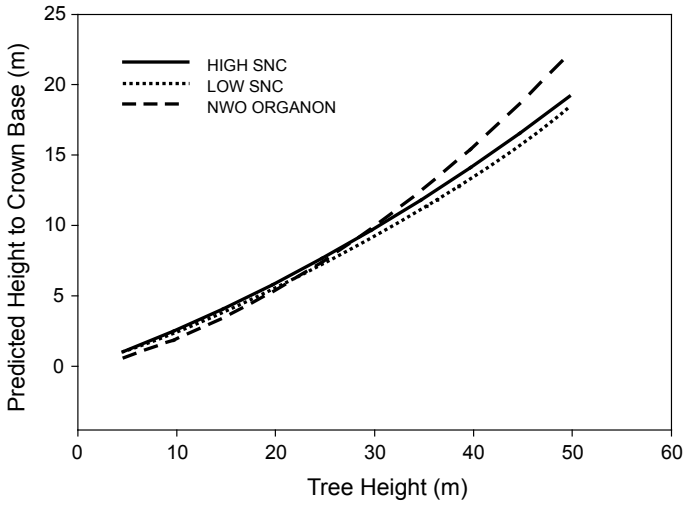

Figure 3. Predicted height to crown base (m) over tree height for high and low levels of SNC. The long dashed line is NWO ORGANON predicted HCB.

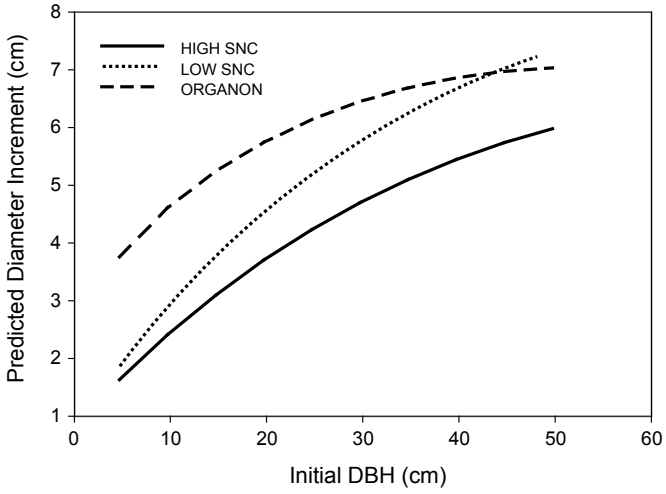

Figure 4. Predicted 5-yr diameter increment over initial DBH for trees with HIGH and lwo SNC. The line with long dashes is SMC ORGANON predicted 5-yr diameter increment when SNC is not acconted for.

5-yr height growth

CLSA ($p<0.0001$) and FOLRET ($p<0.0001$) showed a significant relationship with 5-yr height increment after accounting for potential height growth (ΔPH), crown ratio ($p<0.0001$), CCFL ($p<0.0001$), and tree height divided by predicted stand height (HT/PSH; $p=0.0007$). Compared to an average-sized tree on a plot with low SNC, 5-yr height growth was reduced by 11.4% for a similar sized tree on a plot with high SNC (Figure 5).

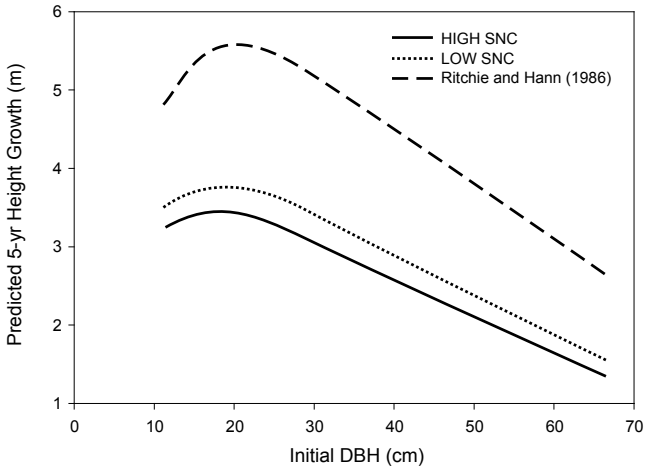

Figure 5. Predicted 5-yr increment (m) over initial DBH for an average stand with high and low SNC. The dashed line is 5-yr increment using the equation presented in Ritchie and Hann (1986).

5-yr mortality rate

Neither plot mean FOLRET or CLSA were significantly related to 5-yr probability of mortality (PM) after accounting for DBH ($p<0.0001$), CR ($p<0.0001$), basal area in larger trees (BAL; $p=0.0499$), CLSA ($p<0.0001$), and the interaction between BAL and CLSA ($p=0.0028$). The equation predicts a decrease in PM with an increase in DBH and CR and an increase in PM with an increase in BAL and CLSA. Unlike Hann et al. (2003), site index was not found to be significantly related to PM after accounting for these variables, while thinning may influence PM as a slight decrease was detected in thinned plots but the inclusion of this variable adversely affected model behavior. More long-term data, particularly from the commercial thinning study, should rectify this and allow for a more valid statistical test of this hypothesis.

Discussion

A significant difference between actual and projected 5-yr stand volume growth existed, indicating that ORGANON needs to be modified in order to accurately accommodate the effects of SNC on tree growth. The greatest bias in individual tree projections was the overestimation of height growth, which is surprising given that SNC tends to reduce basal area more than height growth (Maguire et al. 2003). ORGANON, however, is quite sensitive to initial site index estimates, which in the case of SNC are a reflection of both site potential and the extended effects of the disease. In addition, the significant changes in crown structure due to SNC and the annual variation in disease intensity make growth forecasts under these circumstances quite difficult. ORGANON biases showed a tendency to be significantly related to variables that represented stand structure (QMD, AGE_{BH}), composition (PBA_{DF}, PBA_{WH}), and microclimate (COAST, ASP1), which are all difficult to model effectively because they are variables not usually collected during standard inventories, and in being multidimensional, can lead to an overparameterized model. Thus, the preliminary growth models presented in this analysis follow the typical ORGANON model format with the inclusion of variables representing SNC severity.

The crown sparseness index tended to perform significantly better in the models than foliage retention indicating that it is a more biologically meaningful variable of crown condition. The predictive power of this variable, however, tends to be improved when the sapwood taper model that includes the effects of SNC (Weiskittel and Maguire 2004) is used, which suggests that both crown sparseness and foliage retention should be sampled within a stand. These models can now be incorporated into a stand simulator such as ORGANON, but should be taken with a high degree of caution because of the limited scope of the dataset. These models would be greatly enhanced if measurements on the permanent commercial thinning plots continued. Additional work and data will be needed to refine these preliminary models and incorporate the effects of treatments such as thinning, fertilization, and sulfur spraying.

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Table 3. Equation forms, R^2, and root mean square errors for models presented in this study.

Model	*Model form*	R^2	**MSE**
Stand volume growth bias	$BIAS_{VOL}$ 41.1498 – 3.4098*QMD - 4.4027*AGE_{BH} -2.9846*SI + 22.5351*FOLRET	0.31	31.04
Volume growth correction	$VOLGRTH_{Actual} = 5.7096*VOLGRTH_{Predicted}^{0.5477}$	0.95	19.51
Diameter growth bias	$BIAS_{DG}$ = 4.9731 + 0.0836*QMD – 0.1829*AGE_{BH} -0.1438*SI + 0.7531*FOLRET	0.51	0.92
Height increment bias	$BIAS_{HI}$ = 0.9058 – 0.0223*QMD – 0.8310*PBA_{DF} – 0.0347*SI + 0.0228*COAST + 0.3435*FOLRET	0.41	0.51
Crown recession bias	$BIAS_{CR}$ = 5.0499 – 0.0552*QMD – 3.3556*PBA_{DF} – 2.4813*PBA_{WH} + 0.8239*ASP1 – 0.1369*CLSA	0.52	0.65
5-yr diameter growth (cm)	$\Delta DBH = e^{-0.9009+0.5917*\ln(DBH+5)-0.0112*DBH+0.2869*\ln(SI-1.37)+1.2145*\ln\left(\frac{CR+0.2}{1.2}\right)-0.0512*\frac{BAL}{\ln(DBH+2.7)}-0.2140*\sqrt{BAPH}-0.0071*CLSA-0.0582*CLSA_{TOP}}$	0.71	0.71
5-yr height growth (m)	$\Delta HT = \Delta PH * \left[0.8312 * \{1-\exp(-3.1671 * CR + 0.0122 * CCFL + 0.1592 * CLSA - 0.8179 * FOLRET)\}\right] * [0.3409 * \{(\frac{HT}{PSH}) - 1\}]$	0.51	0.87
5-yr mortality rate	$PM = \left[1.0 + e^{(5.4801-0.41436*DBH-4.6395*CR+0.0271*BAL+0.0325*CLSA-0.0026*(BAL*CLSA)}\right]^{(\frac{PLEN}{5})}$	0.32	0.28
Height to crown base (m)	$HCB = \frac{HT}{1+e^{3.8413-0.0122*HT-0.0070*CCFL-1.1688*\ln(BAPH)+0.4851*\frac{DBH}{HT}+0.0041*SI+0.0931*CLSA_{TOP}-0.0541*FOLRET+0.0039*(SI*FOLRET)}}$	0.95	0.30

*where $BIAS_{VOL}$ is 5-yr volume growth bias (actual – predicted; m^3 ha^{-1}), QMD is stand quadratic mean diameter (cm), AGE_{BH} is stand mean breast height age (yrs), SI is Bruce (1981) site index (m), FOLRET is stand mean foliage retention (yrs.), $VOLGRTH_{Actual}$ is 5-yr actual volume growth (m^3 ha^{-1}), $VOLGRTH_{Predicted}$ is 5-yr volume growth predicted by the SMC variant of ORGANON (m^3 ha^{-1}), $BIAS_{DG}$ is 5-yr bias in diameter growth (cm), $BIAS_{HI}$ is 5-yr bias in height increment (m), PBA_{DF} is the percent of stand basal area in Douglas-fir (%), PBA_{WH} is the percent of stand basal area in western hemlock (%), COAST is the distance from the coast (km), ASP1 is the cosine transformation of slope and aspect [(%slope)*cosine{2 *(aspect/360)}], $BIAS_{CR}$ is 5-yr bias in crown recession (m), CLSA is the crown sparseness index (cm^2/cm), DBH is the diameter at breast height (DBH; cm), HT is the total tree height (HT; m), CR is crown ratio, BAL is the basal area in trees with a DBH larger than the subject tree (m^2 ha^{-1}), BAPH is the stand basal area (m^2 ha^{-1}), $CLSA_{TOP}$ is the stand mean crown sparseness index (cm^2/cm), CCFL is the crown competition factor in trees with a DBH larger than that of the subject tree (m^2 ha^{-1}), PH is potential height (m) calculated from SI and growth effective age (Ritchie and Hann 1986), PSH is Bruce's (1981) predicted stand height (m), PM is probability of tree mortality, and PLEN is the length of the growth period (6 for GIS and PCT plots, 2 for CT plots)

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Growth Response of Young Douglas-fir Plantations with Severe Swiss Needle Cast to Vegetation Management and Balanced Fertilizer Applications

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Introduction

Young Douglas-fir plantations have been shown to respond positively to vegetation management (Crane et al. 2001; Ketchum 2002) and fertilization treatments (Mainwaring et al. 2003) across a gradient of Swiss needle cast severity (SNC). Furthermore, both types of treatments have been shown not to influence disease severity.

Crane et al. (2001) noted a significant positive effect of 16-19% on diameter growth, while Ketchum et al. (2002) observed a 5-14% increase in stem volume depending on the site. Both studies, however, found fertilization to have little or no effect on growth. Following five years of fertilization treatment, Mainwaring et al. (2003) found that the increase in volume growth over control plots amounted to 8.2, 6.1, and 10.2% for N, NPK, and NPKplus treatments, respectively. However, growth responses to fertilization have not been consistent across all sites (Crane et al. 2001).

This study was designed to determine growth response of young Douglas-fir with moderate and severe SNC infection to operational control of competition vegetation and nutrition management.

Methods

Study sites

This study consisted of two trials with each trial having two separate installations on Plum Creek Timber land near Toledo, Oregon. The first trial took place in two 5-10 year old plantations and included, in addition to a control, a treated plot with complete weed control treatment (1-2 aerial applications plus hardwood basal treatment as needed on each site) and a complete nutrition amendment treatment based on foliar nutrient analysis (1-2 aerial applications, depending on nutritional status of the trees). The second trial was located in two 11-15 year old plantations and received a complete nutrition amendment similar to the 5-10 year old plantations.

The experimental design was a randomized block with 3 circular 0.1-ac plots within each experimental unit, resulting in a total of 24 plots in experimental units (2 age classes x 2 sites per age class x 2 treatments per site x 3 plots per treatment).

Field work

All trees within the plot were tagged and measured for diameter at breast height (DBH), total height, and SNC severity in 1998. They were measured every two years since establishment, resulting in two growth periods (98-00, 00-02). Foliage samples were collected between October and January one year after fertilization to determine if there was a shift in foliage nutrient concentrations, content, and mass relative to the controls. Plot characteistics are shown in table 1.

Data analysis

Periodic Annual DBH and height increments were calculated from the three measurements. Stem volume was calculated using Bruce and Demars' equation for second growth Douglas-fir (1974). The growth increments were determined as the difference between successive measurements and analyzed as a split-plot without blocks and age as the whole plot factor. A similar statistical approach was used to assess for differences in plot means of foliage retention by crown level.

Results

Vegetation control + fertilization

Growth

Mean basal area growth showed a positive response to vegetation control + fertilization ($p=0.0176$) after accounting for initial plot top height and measurement period (Figure 1). Mean basal area growth increased 6.7 and 9.3% for the first and second growth periods, respectively. Mean height growth showed a negative response to vegetation control + fertilization ($p<0.0001$) after accounting for installation, measurement period, and the interaction between treatment and measurement period. Height growth was reduced between 3.5 to 33.0%, depending on installation and measurement period. Stand volume growth, however, showed no response to vegetation control ($p=0.5516$) after accounting for initial plot top height, installation, and measurement period.

Foliage retention

Mean foliage retention values in the lower crown third showed a positive response to vegetation control + fertilization ($p=0.0315$; Figure 2), while mean foliage retention values in the upper and middle crown thirds showed no response after accounting for initial plot mean foliage retention. Mean foliage retention in the lower crown increased by 1.7% due to the treatment.

Fertilization

Growth

Mean basal area growth showed no response to fertilization ($p=0.9388$) after accounting for initial plot top height, measurement period, and initial plot mean foliage retention. Mean height growth was significantly influenced by the treatment

Table 1. Attributes of the installations.

AGE/INSTALL	VARIABLE	MEAN	STD	MIN	MAX
5-10 yrs					
Fishing Hole	Stems/ ha	943.12	128.32	691.89	1062.55
	Basal area (m^2)/ha	3.77	0.48	3.20	4.40
	Initial top height (m)	5.09	0.39	4.61	5.51
	Initial foliage retention (yrs)	1.77	0.07	1.67	1.89
Kosydar	Stems/ha	901.93	71.19	815.44	988.42
	Basal area (m^2)/ha	16.29	1.54	14.56	19.12
	Initial top height (m)	4.52	0.28	4.18	4.83
	Initial foliage retention (yrs)	1.79	0.47	1.71	1.86
11-15 yrs					
Fishing Hole	Stems/ ha	720.72	57.24	617.76	766.03
	Basal area (m^2)/ha	16.29	1.54	14.56	19.12
	Initial top height (m)	9.11	0.37	8.54	9.54
	Initial foliage retention (yrs)	1.98	0.08	1.88	2.10
Gas Pipeline	Stems/ ha	518.92	74.95	370.66	568.34
	Basal area (m^2)/ha	24.41	3.16	19.67	28.60
	Initial top height (m)	15.09	0.27	14.71	15.47
	Initial foliage retention (yrs)	1.86	0.13	1.67	2.06

(p=0.0131) after accounting for installation and measurement period. However, its response differed by time since treatment as indicated by the significant interaction between treatment and time (p=0.004). Initially the treatment increased mean height growth by 11.6 to 12.2% during the first measurement period, while decreasing mean height growth by 11.8 to 12.6% in the second measurement period. Consequently, stand volume growth showed no response to the treatment (p=0.3445) after accounting for initial plot top height, initial plot mean foliage retention, and growth measurement period.

Foliage retention

Mean foliage retention values in upper (p=0.0246), middle (0.0008), and lower (p=0.0001) showed a negative response to the fertilization treatment after accounting for initial plot mean foliage retention and initial plot top height (Figure 3). Mean foliage retention values decreased by 6.5, 8.2, and 8.2% in the upper, middle, and lower crown thirds, respectively.

Overall

Over the four-year growth period, neither basal area nor volume growth showed a significant improvement from the treatments. However, 4-yr height growth showed a significant negative relationship (p=0.0197) with the vegetation control + fertilization treatment. In addition, mean plantation foliage retention only showed a significant negative relationship (p=0.0161) with the fertilization only treatment.

Discussion

Similar to other studies on young SNC infected Douglas-fir, vegetation control was found to significantly increase basal area growth, but fertilization had a minimal impact on growth. Unfortunately, the effects of either just vegetation management or fertilization on volume growth in the younger plantations can't be separated because of the study design. The gains in diameter growth were similar to those reported by Ketchum et al. (2002) for the coastal site located near the installations used in this study. Furthermore, the reduction in height growth due to the treatment is similar to the findings for the east-Coast Range site, but they attributed this to tip frost damage rather than a treatment effect (Ketchum et al. 2002). On the other hand, this

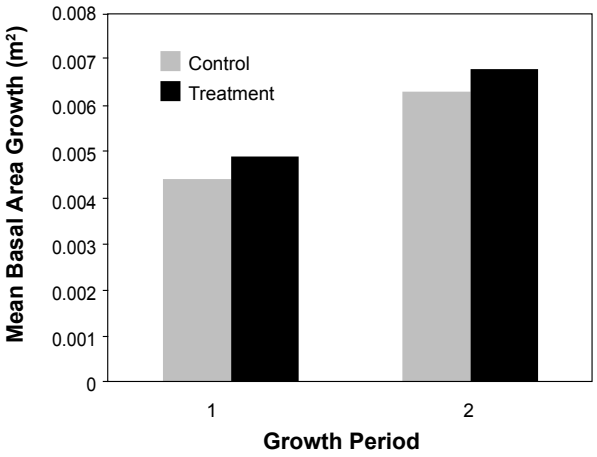

Figure 1. Influence of vegetation management + fertilization on basal area growth over two measurement periods.

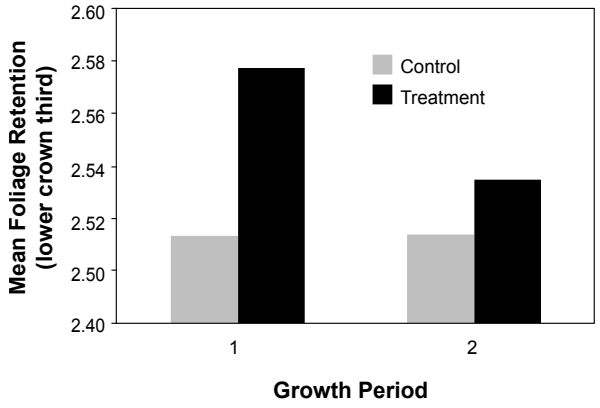

Figure 2. Influence of vegetation management + fertilization on mean foliage retention values in the lower crown third over two measurement periods. Changes in foliage retention values in the upper and middle crown thirds were not significantly influenced by the treatment.

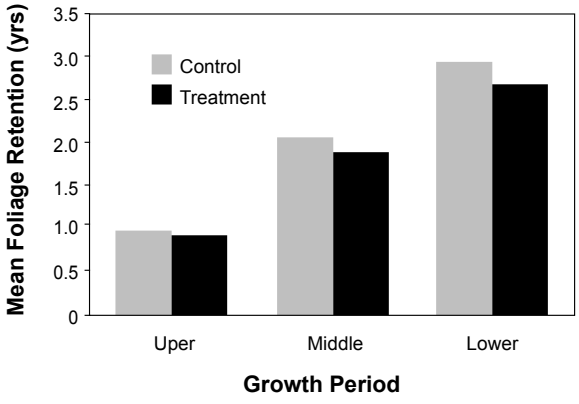

Figure 3. Mean foliage retention value for the control and fertilization plots by crown third.

reduction in height growth may indicate a reallocation of resources towards rebuilding crown lost to the disease as suggested by the improvement of foliage retention values in the lower crown.

Fertilization had a minimal influence on growth with both basal area and volume growth showing no response. Height growth showed an initial response to the treatment, but had a negative response in the second growth period, which may be due to the reduction in needle retention values for all crown levels due to the treatment. This lack of response is similar to the findings of Carter et al. (1998) as they found only 25% of their 48 experiments showed a significant positive response in basal area growth 3 years after various fertilization treatments across a range of Douglas-fir stand conditions in coastal British Columbia. Similarly, only 10% of their experiments showed a significant fertilizer effect on height growth 6 years after treatments with two of these being a negative effect (Carter et al. 1998).

Although Ketchum et al. (2002) and Mainwaring et al. (2003) found no consistent patterns in needle retention by fertilizer treatment, other studies have consistently found fertilization to decrease foliage retention levels (Brix 1981; Balster and Marshall 2000), which has been attributed to faster self-shading rates and reduced needle construction costs. In the case of SNC, the reduction of foliage retention values maybe due to the interaction between the treatment and disease.

Conclusion

The combination of vegetation control and fertilization in young plantations (5-10 yrs old) appears to moderately improve basal area growth, but not height or volume growth. In addition, this type of treatment seems to improve foliage retention levels in the lower crown, while significantly reducing height growth. Improved foliage retention in the young plantations may have largely been an effect of reducing leaf area of the competing vegetation rather than fertilization. However, fertilization in 10-15 year old plantations does not have an influence on growth and reduces foliage retention values in all crown levels. Furthermore, the inability to separate the effects of vegetation control and fertilization in these stands means that the efficacy of fertilization alone remains unanswered by this study.

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Menasha Silvicultural Trials: Response of SNC-impacted Douglas-fir to Intensive Silvicultural Treatments

Doug Mainwaring, OSU; Jim Carr, Menasha; Doug Maguire, OSU

Abstract

The Menasha/COPE research plots were installed in the winter of 1993/94 with the objective of investigating the effects of pre-commercial thinning, pruning, and nitrogen fertilization treatments in young Douglas-fir. Established in 10-year old Douglas-fir plantations south of Coos Bay, Oregon, Swiss needle cast levels in the four replicates have since increased, creating the opportunity to test the responses to these treatments in the presence of SNC. After the recent 10-year remeasurement, Swiss needle cast intensity and treatment effects were analyzed. None of the treatments had any effect on current foliage retention, though crown sparseness (CL: SA) was significantly lower on PCT'd plots, and the decreased CL: SA with fertilization was marginally significant. There was no significant effect of fertilization on basal area growth, volume growth, form quotient, or stem cross-sectional growth at 13 ft of height. Pre-commercial thinning significantly increased basal area growth over the period from year 4 to year 10. Pruning was associated with a lower basal area and volume growth over the 10-year period.

Introduction

The Menasha thinning study was initiated in 1992 under the auspices of the Coastal Oregon Productivity Enhancement (COPE) Program. The goal of this program was to enhance the economic and social benefits derived from the Oregon Coast Range through a better understanding of its resources and how to utilize them. Among the goals of this program was investigating the advantages to be gained from intensive silvicultural treatments in young Douglas-fir plantations. Accordingly, this replicated study included pre-commercial thinning, pruning, and fertilization treatments.

With the emergence of Swiss needle cast (SNC) as a damaging disease of Douglas-fir on the Oregon coast, concerns have been raised about the effect of standard silvicultural treatments on tree growth and disease development. Because much of the Coast Range is privately owned, and presently managed for high yield timber production, the question of whether the standard silvicultural

treatments of an intensive management regime are effective in the presence of SNC is of fundamental importance.

A previous study looking at the effect of pre-commercial thinning in infected stands found that thinning had no effect on the foliage retention of infected stands (Kanaskie et al. 2002b), and that the volume growth of trees showed a positive response (Kanaskie et al. 2002a). The effect of pruning in SNC infected stands has not been investigated.

Of particular interest from this study is the fertilizer response. Although fertilization is an accepted tool of intensive Douglas-fir silviculture, it has been called into question in SNC infected stands. Results of fertilization in infected stands have thus far been mixed. Treatments of nitrogen and NPK blends in stands covering a range of SNC-infection levels resulted in a positive volume growth response (Mainwaring et al. 2003). Other studies in young plantations have found little or no response to nitrogen additions (Crane et al. 2001, Ketchum et al. 2002, Rose and Rosner 2004). In an Idaho study, fungal fruiting, and thus disease severity increased with addition of nitrogen fertilizer (El-Hajj et al. 2004).

The response of the treatments on the Menasha plots will thus provide additional information in the ongoing debate about the value of fertilization. The objectives of this analysis are to investigate the effect of the treatments on the current levels of SNC and the growth and form of the residual trees.

Methods

The study plots were established in 1994 in 10-year old (breast height) Douglas-fir plantations. The site is located about 10 miles south of Coos Bay, Oregon, on land owned by the Menasha Corporation. Plot averages for the four replicates are shown in table 1.

Four replications were established within a few miles of one another, each containing six treatments. Plots were 0.25 acres in size with a 20-foot buffer. The treatments were:

1) PCT, Prune, fertilized
2) PCT, Prune not fertilized
3) PCT, fertilized
4) PCT, not fertilized
5) Fertilized
6) Not fertilized

Plots were fertilized with a total of 400 lbs/acre of nitrogen (urea): the first application of 200 lbs/acre was made in the winter of 1993-94, and the second application of 200 lbs/acre was made in the winter of 1997-98.

Pre-commercially thinned stands were thinned to between 250 and 270 trees per acre, and pruned stands were pruned in two lifts, first to 13, and finally to 20 feet.

Plots were measured at establishment, after 4 years of growth, and after 10 years of growth. All trees were measured for dbh, and every fifth numbered tree was measured for height and height to crown base. The diameter at 13 feet was measured on height trees of acceptable form on treatments 1-4. SNC variables were collected at year 10: height trees were cored for sapwood width, and branches were sampled for foliage retention. Foliage retention was measured on two cut branches per tree. These branches were sampled from opposite sides of the tree at the fifth whorl, or as close to the fifth whorl as possible.

Table 1: Plot characteristics

Trt	Treatment description	QMD year 0 (cm)	QMD year 10 (cm)	Height year 0 (m)	Height year 10 (m)	HCB, year 0 (m)	HCB, year 4 (m)	HCB, year 10 (m)	Foliage Retention (years)	CL:SA (cm/cm^2)	BAgrowth (m^2/ha) (10 y)	VOLgrowth (m^3/ha) (10 y)	Form quotient year 4	Form quotient year 10
1	PCT, prune, fert	12.6	23.5	8.5	16.07	4.18	4.18	6.23	2.32	6.49	17.99	143.2	0.85	0.91
2	PCT, prune, no fert	12.5	23.7	8.35	16.22	4.24	4.28	6.2	2.58	7.47	17.33	145.5	0.86	0.89
3	PCT, fert	12.4	24.7	8.54	16.42	1.21	2.3	6.04	2.57	6.83	20.47	159.4	0.83	0.88
4	PCT, no fert	12.2	24.6	8.57	16.67	1.13	2.67	6.98	2.82	7.38	22.03	175.8	0.83	0.88
5	Unthinned, fert	9.1	17.6	6.4	16.53	1.3	4	7.87	2.65	8.54	19.21	181.2	NA	NA
6	Unthinned, no fert	9.1	17.9	6.46	16.88	1.49	4.04	8.23	2.7	9.09	20.08	192.2	NA	NA

Treatment effects were analyzed using regression techniques.

Results

Foliage Retention

Average foliage retention for each block is shown in table 1. After accounting for block effects, there is no significant difference in foliage retention with fertilization. Similarly, pre-commercial thinning and pruning are not associated with any differences in foliage retention.

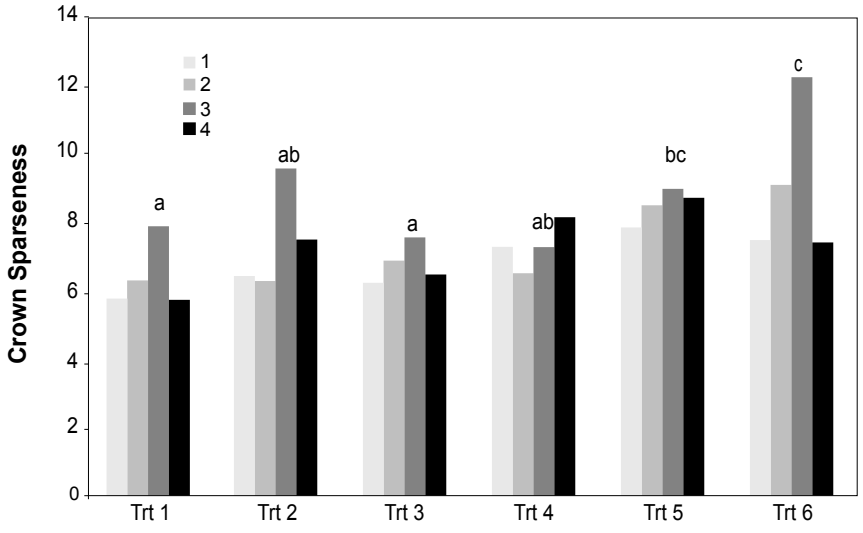

Figure 1: Crown sparseness (CL:SA) by replication and treatment. Treatments with the same letter are not significantly different (p<0.05).

Crown Sparseness

Average crown sparseness (CL:SA) on each plot is shown in figure 1. After accounting for block effects, there is a marginally significant decrease of crown sparseness with fertilization of 0.69 cm/cm^2 (table 2). Crown sparseness is significantly lower on PCT'd plots than unthinned plots (table 2). Crown sparseness on pruned plots doesn't differ significantly from that of unpruned plots.

Basal Area Growth

After accounting for block effects, Douglas-fir basal area, and basal area from other species, fertilization was found to have no effect on Douglas-fir basal area growth for any of the treatment combinations.

Using the same covariates, Douglas-fir basal area growth was found to respond positively to pre-commercial thinning over the period from year 4 to year 10, but not the entire period, indicating that the increase depended on the buildup of crown.

By contrast, pruning was found to have a negative effect on basal area growth over the entire period, though not from year 4 to year 10. Inclusion of crown ratio in the equation rendered pruning insignificant over the ten-year period (table 2).

Volume Growth

After accounting for block effects, Douglas-fir basal area, and basal area from other species, volume growth was not significantly affected by either fertilization or pre-commercial thinning.

Table 2: Regression p-values

Variable	Covariates	Treatment	Period	
			year 10	
Foliage Retention		Fertilization	NS	
		PCT	NS	
	Block effects	Prune	NS	
Crown Sparseness		Fertilization	0.078	
		PCT	0.001	
	Block effects	Prune	NS	
			Year 0-year 10	Year 4-year 10
Basal area growth	Block effects	Fertilization	NS	NS
	Douglas-fir BA	PCT	NS	0.003
	non-Douglas-fir BA	Prune	0.002	NS
Volume growth	Block effects	Fertilization	NS	NS
	Douglas-fir BA	PCT	NS	NS
	non-Douglas-fir BA	Prune	0.015	NS
Form quotient	Block effects	Fertilization	NS	NS
	Douglas-fir BA	PCT	NS	NS
	non-Douglas-fir BA	Prune	NS	NS

Volume growth over the entire 10-year period was negatively affected by pruning, though this effect was insignificant over the period from year 4 to year 10 (table 2). As with basal area growth, addition of crown ratio to the equation rendered pruning an insignificant factor in explaining volume growth.

Form

Diameter measurements at 13 ft of height enabled the calculation of form quotient (DOB_{13}/DBH). Accordingly, this variable was tested for treatment differences at year 4 and year 10. At year 4, form quotient was significantly higher for pruned trees than unpruned trees, though overall correlation was low (R^2=0.11). This result is not surprising given the significant difference in height to crown base as a result of the pruning (ANOVA), still present at year 4 (table 1). By year 10, there were no significant differences between pruned and unpruned plots for either form or height to crown base.

Stem cross sectional growth at 13 feet between year 4 and 10 was also analyzed for treatment differences, but none was found.

Discussion

One drawback of the Menasha plots is the lack of initial SNC data with which to monitor changes in the disease attributable to treatment. Nevertheless, with four blocks in the same stand, it is likely that the initial SNC intensity between plots was similar.

Although previous work in fertilization of Douglas-fir suggests that fertilization reduces foliage retention (Balster and Marshall. 2000), the fact that foliage retention on fertilized plots is not significantly different from non-fertilized plots suggests that SNC, rather than fertilization is probably the limiting factor. Still, other studies have found significant negative correlation between nitrogen fertilization and foliage retention in infected areas (Rose and Rosner. 2004).

In healthy Douglas-fir stands, the primary crown effect of nitrogen fertilization is an overall increase in foliar biomass, and hence, leaf area (Brix and Ebell. 1969). Because there are no differences in crown length between fert/no fert treatment pairs (ANOVA), any increase in leaf area (sapwood area) should be reflected in smaller CL:SA values. Although there is a marginally significant densification of crowns with fertilization, the response is very variable. Previous sampling for CL:SA has been done such that trees spanning the diameter distribution were sampled. Because this study used a systematic sample, some plots didn't cover the range of diameters as well, calling the marginal significance of this result into further question.

The lack of a significant growth response to fertilization is similar to what was found for similarly-aged trees in the Plum Creek dataset (Weiskittel et al. 2004). Studies in younger stands have found little or no significant volume growth response to fertilization (Rose and Rosner 2004, Ketchum 2002). In contrast, Mainwaring et al. (2003) found a positive volume growth response to fertilization of 6-10%, depending on treatment, over a five-year period in stands ranging from 5 to 27 years of age. This latter study included a 200 lb/acre nitrogen treatment in addition to NPK and NPK plus micronutrient treatments, all of which gave a positive response.

Pre-commercial thinning has already been established as an effective way to boost basal area and volume growth in SNC-impacted stands (Kanaskie et al. 2002a, Kanaskie et al. 2002b), a result per unit of growing stock reinforced by this study.

Pruning, while temporarily diminishing basal area and volume growth by crown removal, is not, and should not be used in SNC-infected stands. Pruning is best employed in stands able to produce a significant amount of diameter growth after pruning—on well spaced, high site trees. The growth loss resulting from SNC disqualifies these stands as candidates for pruning. Pruning was included in this study before SNC became a problem on the south coast.

Conclusion

Fertilization did not significantly affect basal area or volume growth, in thinned or unthinned plots. Although a non-response to nitrogen fertilization in SNC-impacted stands is not a universal result, an increasing number of studies are not finding a response. This result, in addition to evidence that nitrogen applications may only be serving to feed the fungus, provides a cautionary backdrop to nitrogen fertilization projects.

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Interactive Effects of Swiss Needle Cast and Commercial Thinning on Douglas-fir Growth and Development in North Coastal Oregon—Results from the First 15 Permanent Plots

Doug Mainwaring, OSU; Doug Maguire, OSU; Alan Kanaskie, ODF; and Jeff Brandt, ODF

Introduction

Many Douglas-fir (*Psuedotsuga menziesii*) stands in western Oregon are suffering from Swiss needle cast (SNC), a foliage disease caused by the fungus *Phaecryptopus gaeumannii* (Hansen et al. 2000). Although this fungus is endemic throughout the range of coastal Douglas-fir (Boyce, 1940), there have been noted increases in fungal presence, infection incidence, disease symptoms, and associated negative growth effects in the last 10 years (Hansen et al. 2000). A recent aerial survey indicated that approximately 108,000 hectares out of the 1.2 million ha surveyed in Oregon showed detectable discoloration, a decrease from the previous high of 157,000 hectares in 2002 (Kanaskie et al. 2003).

Of greatest concern are the approximately 76,000 hectares of 10-30 year old plantations in north coastal Oregon. These plantations exhibit various degrees of SNC infection, but severe SNC may prevent them from attaining merchantable size. An ongoing six-year study of this population has found that stands with the most severe levels of infection are experiencing a cubic volume growth loss of approximately 52%, with a population average of 21% volume growth loss (Maguire et al. 2002). Some heavily infected stands at the low end of this age range, believed to be growing so poorly that they have no chance of becoming merchantable, have been underplanted or cleared and replanted with non-susceptible species, in most cases western hemlock (*Tsuga heterophylla*).

Where heavily infected stands have reached merchantable size, the standard silvicultural prescription among industrial forest landowners is to clearcut the diseased Douglas-fir, and replant the stand to a mix of non-susceptible species and lesser amounts of Douglas-fir. Regeneration harvesting has usually been done in stands with tree size and value sufficient to cover costs of the operation. In these stands, thinning has been avoided as a tool to improve crown vigor because field observations and limited data suggest that thinning stands with severe Swiss needle cast may accelerate symptom development and associated growth declines.

In younger stands, previous work has suggested otherwise. A study undertaken in a stand of infected Douglas-fir in New Zealand indicated that thinned trees had similar infection rates and developed deeper crowns, but did not have significantly less foliage than unthinned trees five years after thinning (Hood and Sandberg 1979). Another New Zealand study investigated the effect of different levels of thinning on basal area growth in infected stands, but the results were inconclusive (Manley 1985, unpublished). While more recent work indicates that pre-commercial thinning of SNC-infected Douglas-fir even under severe SNC does not intensify disease development in younger stands (Kanaskie et al. 2002), the thinning response of older stands (30-60 yrs old) with varying degrees of Swiss needle cast damage is largely unknown.

Most industrial forest landowners are not thinning commercially on sites with significant levels of SNC. However, the Oregon Department of Forestry (ODF), by virtue of its large holdings of commercial timber in the SNC zone, state-mandated priorities, and current management objectives, must rely more heavily on thinning. The largest concentration of state-owned timberland, the 147,000-ha Tillamook State Forest, is on the northwestern Oregon coast, where SNC is especially problematic. This relatively homogeneous forest is the result of a massive reforestation effort following four major fires, which burned almost 144,000 ha from 1933-1951 (Fick and Martin 1993). In the approximately 95,000-ha Tillamook district of the Tillamook state forest, 70% of the land base is conifer forest between 26 and 55 years old and almost all of the growing stock is Douglas-fir. Stand densities need to be reduced to maintain health and future options, so thinning is a key component of the state's structure-based management plan (Oregon Dept. of Forestry 2001). Designed to meet changing public priorities, the new management guidelines call for 40-60% of each district's land base to be made up of stands having a layered, or two-storied structure (Oregon Dept. of Forestry 2001). Qualitative description of the structural components necessary to meet the criteria for these layered stands suggests that thinning will be an essential tool to produce the required structural diversity. However, SNC may be a serious obstacle to meeting these objectives.

A retrospective phase of this study, completed last year, looked at the thinning response of stands treated 4 to 10 years prior. These stand, were distributed across a large range of SNC infection levels, stand densities, and locations. The most heavily infected stands experienced a 36% volume growth loss relative to healthy stands that were also thinned, but basal area growth responded positively to treatment. In addition, results indicated that heavier thinning was associated with a greater response, an expected result in healthy stands, but long in question where SNC is severe (Mainwaring et al. 2003). Due to the retrospective nature of the study, these results depended on the assumption that thinning did not exacerbate SNC intensity.

With installation and monitoring of paired permanent plots in this second phase of the study, the assumption of no change in SNC severity could be tested. The paired permanent plots, one thinned and one control, also targeted 30-60 year old stands with a wide range of locations, initial densities and SNC symptoms. The objective was to test the following hypotheses: 1) Thinning increases SNC symptom severity; 2) Response of SNC symptoms to thinning depends on initial SNC severity; 3) Thinning causes a reduction in individual tree volume growth; and 4) Volume growth losses after thinning increase with initial intensity of SNC.

Methods

The study sites were distributed across five different northwestern Oregon ODF districts (Tillamook, Forest Grove, Astoria, West Oregon, Santiam), four of which include land in the Coast Range.

Fifteen pairs of fixed area plots were established during the winter of 2001 (Table 1). These plots were measured during the dormant season. Plot locations were distributed across a range of disease severity classes and initial densities, and included different aspects and slopes. Target stands were 30 to 60 years of age, had at least 75% of the basal area in Douglas-fir, and were scheduled for thinning prior to May 2002. Plot locations were chosen from among candidate timber sales provided by the five ODF districts.

In a representative part of each stand, two square, 0.2 ha (0.5 ac) plots were established, each with its own 21 m buffer, for a total of

Table 1: Plot characteristics

Plot	Trt	ODF dist.	Volume PAI (ft^3/acre)	Site index (ft/50y)	RD (at thin) ($ft^2/ac/in^{0.5}$)	QMD-DF (at thin) (in.)	Foliage retention (yrs)	CL:SA (cm/cm^2)	Douglas-fir basal area (ft^2/ac)	Non-DF BA (ft^2/ac)	Age (yrs)
Brownsmead	Cont	Ast	16.8	46.1	64.7	31.2	2.0	5.81	38.3	13.9	32.2
Brownsmead	Thin	Ast	13.7	46.1	32.7	34.8	2.07	5.01	27.7	0.1	31.7
Clammer	Cont	Till	14.5	44.6	65.1	30.2	1.95	4.89	36.6	15.0	29.0
Clammer	Thin	Till	6.9	42.6	27.8	32.3	1.85	5.49	19.5	3.3	34.0
Cook-Wright	Cont	Till	13.8	40.9	63.6	25.7	1.75	8.28	34.9	11.5	29.2
Cook-Wright	Thin	Till	5.0	39.1	24.8	29.2	2.21	7.04	13.7	5.6	28.3
Fall Hatch	Cont	WO	18.0	40.2	68.5	46.2	2.0	5.47	66.7	0.4	60.1
Fall Hatch	Thin	WO	7.5	40.5	22.4	62.0	2.0	6.95	25.4	0	60.4
Gales Creek	Cont	FG	18.3	43.4	53.2	42.7	3.88	4.42	47.2	2.9	47.5
Gales Creek	Thin	FG	10.9	43.9	29.2	49.5	3.70	5.39	29.7	0	48
Gold Peak	Cont	Till	17.8	42.6	46.1	38.4	2.0	4.71	41.1	0	32.8
Gold Peak	Thin	Till	11.9	40.9	43.4	38.5	2.0	4.96	37.4	0	31
Hagg Lake	Cont	FG	23.8	40.8	64.9	35.1	4.25	5.24	55.4	0	44
Hagg Lake	Thin	FG	14.1	39.5	31.6	41.9	4.3	3.7	29.5	0	42.2
Kilchis Lookout	Cont	Till	198.8	123.8	63.7	9.9	1.38	7.17	200.4	0	32.7
Kilchis Lookout	Thin	Till	7.8	39.9	39.1	26.7	1.65	6.51	29.2	0	30.0
Lower wolf	Cont	WO	23.2	47.5	72.6	49.8	3.3	4.80	69.6	4.2	54.3
Lower wolf	Thin	WO	11.0	46.4	29.8	59.7	2.65	5.51	33.2	0	55.6
Miami stu	Cont	Till	13.7	37.8	44.9	37.6	1.33	4.36	35.8	4.0	33.8
Miami stu	Thin	Till	5.4	37.6	25.6	38.4	1.45	5.07	17.5	5.3	32.6
Sam downs	Cont	Till	10.7	38.2	57.3	26.2	1.46	5.39	38.4	3.8	31.3
Sam downs	Thin	Till	97.2	40.5	38.3	27.9	1.3	6.49	24.7	4.5	32.1
Soapstone	Cont	Ast	13.9	43.3	64.0	32.8	1.9	7.54	44.2	8.6	34.8
Soapstone	Thin	Ast	11.5	44.7	42.8	33.0	1.75	8.52	35.3	0	33.0
Toll road	Cont	Till	16.5	41.4	47.0	33.5	1.85	4.38	37.6	1.6	28.3
Toll road	Thin	Till	7.6	42.3	26.3	33.3	1.45	4.52	19.2	2.6	29.4
Tom rock	Cont	Sant	13.2	36.5	71.4	32.8	3.2	9.70	54.1	4.6	59.4
Tom rock	Thin	Sant	10.0	40.2	37.9	39.9	3.2	10.08	31.6	2.9	59.8
Westport	Cont	Ast	21.6	43.7	54.2	34.0	3.55	5.35	40.4	5.2	27.8
Westport	Thin	Ast	18.3	41.6	33.6	38.1	3.45	4.56	29.8	0	26.4

a 0.8 ha treatment area. Where possible, the treatment plot was contiguous to the control plot. Measurements were confined to the inner 0.2-ha square. Prior to thinning, all trees >5 cm on the treatment plot were marked at breast-height with a paintstik and measured for DBH (nearest 0.1 cm). When thinning had been completed, all trees > 5 cm on both plots were tagged and measured for dbh, with the tags on the treatment plot placed on the paintstik mark. A subsample of 40 Douglas-fir were measured for total height and height to lowest live branch (nearest 0.01 m). This subsample included the 10 largest Douglas-fir by dbh and the 4 smallest by dbh, with the remaining 26 distributed evenly across the diameter range of the plot. The 5-10 largest Douglas-fir were cored at breast height for sapwood width. Sapwood area at crown base was estimated using a previously constructed sapwood taper equation for Douglas-fir (Maguire and Batista 1996). In addition, ages were obtained for the 10 largest Douglas-fir. Foliage retention on the 5-10 largest trees provided an estimate of SNC infection severity. The standard SNC rating is the number of years that foliage is retained, averaged across the upper, middle and lower third of the crown. Due to the height of crowns and associated visibility problems in these older, larger trees, a single rating was given for the whole tree, based on the average retention of the entire crown.

Analysis

To test whether thinning affected foliage retention, the data were analyzed as a randomized block experiment, adjusted for covariates. Each pair of plots was a block with one control and one thinned plot. Numerous covariates were combined with these categorical variables, including initial foliage retention, initial crown sparseness (live crown length (cm)/sapwood area at crown base (cm^2); Maguire and Kanaskie 2002), site index, and variables representing initial density and thinning intensity.

To isolate the "effect" of initial SNC severity on growth response to thinning, periodic annual volume growth was regressed on foliage retention and crown sparseness, in addition to other covariates that typically influence stand growth. The latter variables included Douglas-fir basal area, basal area of other species, site index, relative density, quadratic mean diameter, crown ratio, crown length, age, and indicator variables representing location and site effects.

Results

Change in Foliage retention

In general, the direction of change in foliage retention was similar for both thinned and unthinned plots within a block (figure 1). Any measured changes at the block level were apparently the result of local infection levels rather than treatment, as indicated by ANOVA.

However, when analyzed as a randomized block experiment with covariates, both block and treatment effects were significant in explaining the change in foliage retention (R^2=97%). The covariates included initial foliage retention and a treatment*foliage retention interaction term, indicating that the change in foliage retention on thinned plots (vs. controls) depends on the initial level of foliage retention (figure 2).

Because there was significant between-block variation due to factors such as site index, stand density, and SNC infection levels, replacement of block effects with variables describing these differences make it possible to expand inference beyond these plots. Approximately 51% of the variation in the change in the logarithm of foliage retention was explained by the following model (MSE = 0.0536):

[1] $(dFOLRET) = a_0 + a_1(BADF) + a_2(FOLRET) + a_3(CLSA) + a_4 (CUTBA)$

where dFOLRET = Change in foliage retention (years)
BADF = Douglas-fir basal area (m^2/ha)
FOLRET = Current average foliage retention for the plot (yrs)
CLSA = Crown sparseness (cm/cm^2)
CUTBA = Removed basal area (m^2/ha)

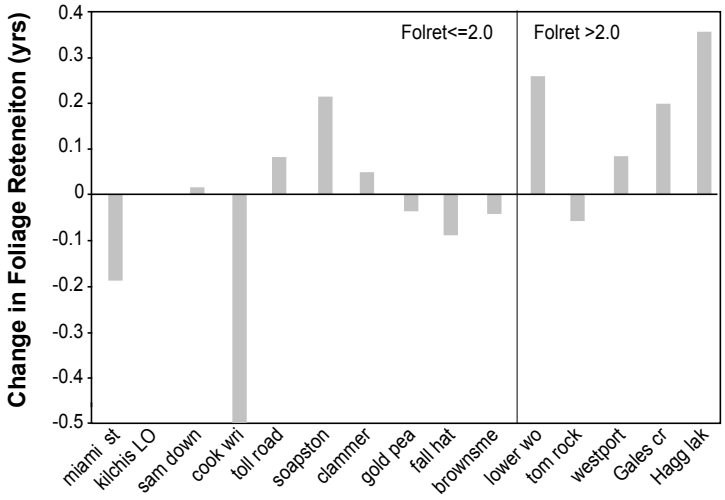

Figure 1. Change in foliage retention for thinned plots vs. controls: plot summary.

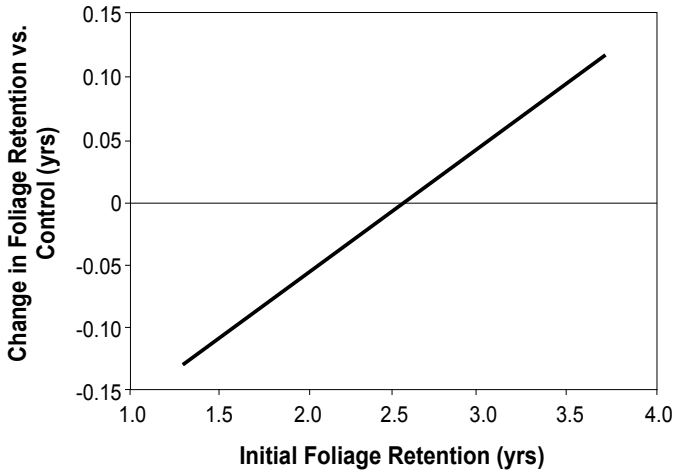

Figure 2. Change in foliage retention for thinned plots vs. controls implied by parameter values from randomized block analysis

Table 2. Parameter estimates for model describing the change in foliage retention (equation [1]).

Variable	Parameter Estimate	Standard Error
a_0	-0.27507	0.24157
a_1	-0.01783	0.00495
a_2	0.21974	0.05448
a_3	0.07964	0.02807
a_4	-0.01372	0.00461

Parameter estimates (table 2) indicated that foliage retention increased with higher initial foliage retention and lower crown sparseness, and decreased with increased Douglas-fir basal area and thinning intensity. The parameter value for CUTBA indicates that every additional 4.6 m^2/ha (20 ft^2/ac) of basal area removed is associated with a loss of 0.063 years of foliage retention.

Although the residual plot did not indicate the presence of any extreme outliers, one of the plots is very influential, to the extent that dropping it renders BADF and CUTBA in equation [1] insignificant.

Change in crown sparseness

As with foliage retention, block effects were evident for change in crown sparseness, with a mix of responses to treatment. ANOVA without covariates indicated that while there were block-level differences, no treatment effect was evident (figure 3). When analyzed as a randomized block experiment with CUTBA as a covariate, treatment was significant and block was marginally significant (p=0.078) in explaining

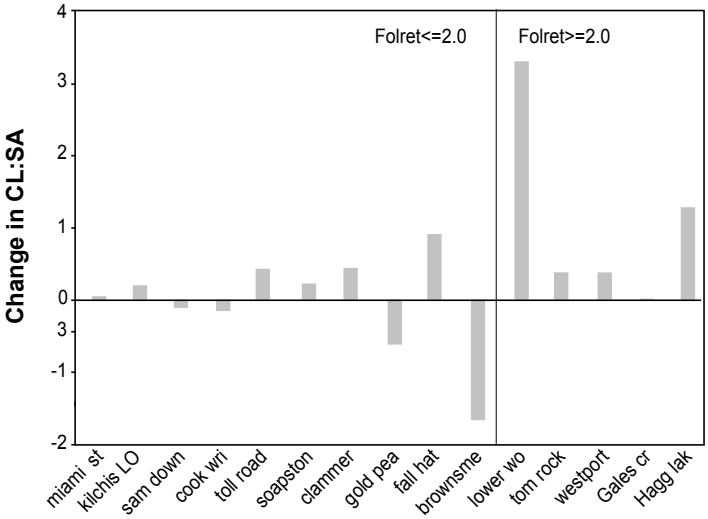

Figure 3. Change in crown sparseness for thinned plots vs. controls: plot summary.

the change in crown sparseness (R^2=82%). As the basal area removed increased, the crowns became significantly sparser.

When analyzed with regression techniques, approximately 45% of the variation in the change in crown sparseness was explained by the following model (MSE = 0.667):

[2] $(dCL:SA) = b_0 + b_1(THIN) + b_2\ln(CR) + b_3\ln(CUTBA)$

where dCLSA = Change in foliage retention (years)
THIN = 1 if plot was thinned, 0 if not
CR = Crown ratio (as proportion)
CUTBA = Removed basal area per acre (m^2/ha)

Parameter estimates (Table 3) indicated that the change in crown sparseness is increasingly positive as average crown ratio decreases and more basal area is removed. In two stands with similar crown ratios, crowns in thinned stands remained denser than crowns in controls stands when less than 15.3 m^2/ha (66.5 ft^2/ac) of basal area was removed. At higher levels of removal, crowns in thinned stands became sparser than in controls.

Table 3. Parameter estimates for model describing the change in foliage retention (equation [2]).

Variable	Parameter Estimate	Standard Error
$\mathbf{b_0}$	19.49346	8.66180
$\mathbf{b_1}$	-23.50885	9.95111
$\mathbf{b_2}$	-1.58944	0.81261
$\mathbf{b_3}$	1.24748	0.51933

Periodic volume increment

Treated as a randomized block experiment, both plot and treatment effects were significant in explaining volume increment. Plot attributes varied considerably (Table 1), underscoring the need to account for covariates other than those representing SNC severity. Volume growth since thinning was significantly related to its initial SNC index and other covariates reflecting site quality, stand density, and thinning intensity. Approximately 93% of the variation in the logarithm of periodic annual volume increment was explained by the following model (MSE = 0.0160):

[3] $\ln(VPAI) = c_0 + c_1\ln(BADF) + c_2(RD) + c_3\ln(SI) + c_4(FOLRET) + c_5(CUTBA) + c_6(THIN) + c_7(TFOLRET)$

where VPAI = Periodic volume increment per acre (m^3/ha/yr)
BADF = Douglas-fir basal area (m^2/ha)
RD = Relative density (Curtis 1982)
SI = 50 yr site index (m) (Bruce 1981)
FOLRET = Current average foliage retention for the plot (yrs)
CUTBA = CUT basal area, all species (m^2/ha)
THIN = 1 if plot was thinned, 0 if not
TFOLRET = Interaction term: THIN * FOLRET

Parameter estimates (Table 4) indicated that periodic annual volume increment increased with increasing Douglas-fir basal area, site index, and foliage retention, and decreased with increasing relative density, cut basal area, and thinning. Total RD accounts for competition from other species.

Periodic annual volume increment varies significantly depending on initial foliage retention, initial Douglas-fir basal area, and whether or not it has been thinned. The significance of the foliage retention and thinning interaction indicates that the negative effect of thinning on stand volume growth depends on the level of SNC. This negative effect is greater as foliage retention decreases (figure 4).

Without thinning, Douglas-fir continues to produce significant volume growth even where Swiss needle cast levels are high. When compared to an uninfected stand (represented here by foliage retention averages from Gales Creek, Hagg Lake, Westport, and Tom Rock, 3.7 years), growth losses at the lowest foliage retentions don't exceed 17%. In contrast, a thinned stand with a foliage retention of 1.3 years would, all else being equal, grow 37% less cubic volume than a thinned stand with a foliage retention of 3.7 years (figure 5).

In order to determine how individual trees are responding to treatment, a model was constructed using the subset of trees which had been measured for height and height to lowest

Table 4. Parameter estimates for model describing periodic annual volume increment (equation[3]).

Variable	Parameter Estimate	Standard Error
c_0	-5.85581	1.32350
c_1	0.68205	0.13902
c_2	-0.01169	0.00428
c_3	1.76462	0.36835
c_4	0.07468	0.03771
c_5	-0.01488	0.00366
c_6	-0.45715	0.15201
c_7	0.11785	0.05258

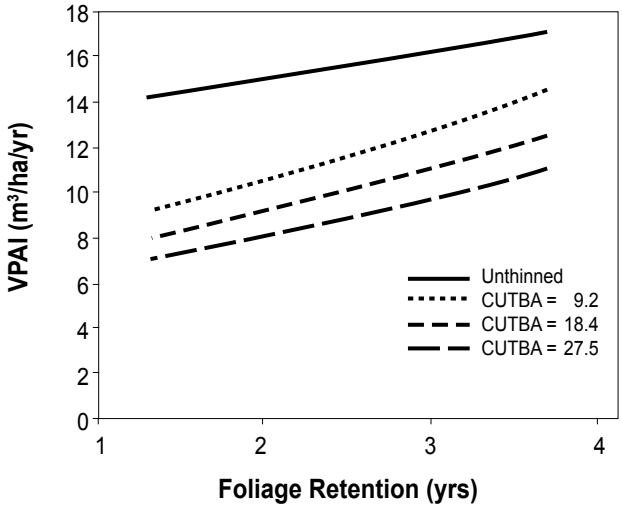

Figure 4. Periodic annual volume increment implied by model [3], assuming mean values for Douglas-fir basal area (25.9 m^2/ha), RD (31), and site index (41.1 m, 50 yrs.). Removed basal area is in m^2/ha.

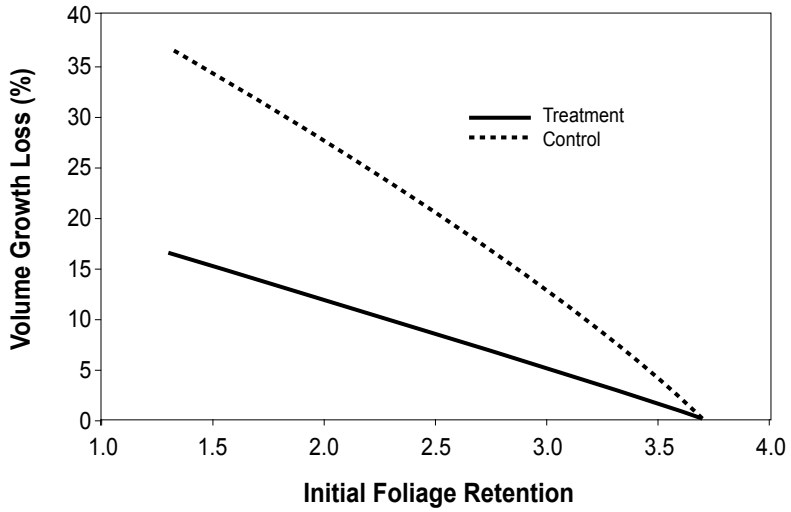

Figure 5. Volume growth loss by foliage retention and treatment type.

live branch on each plot. Approximately 81% of the variation in the logarithm of periodic annual volume increment was explained by the following model (MSE = 0.2520):

[4] $\ln(VPAI) = d_0 + d_1\ln(DBH) + d_2\ln(CR) + d_3(BAL) + d_4\ln(SI) + d_5\ln(BAtotal) + d_6(CUTBA) + d_7\ln(FOLRET) + d_8(THIN) + d_9(TLD) + d_{10}(TBAL) + d_{11}(TFLD) + d_{12}(CFLD)$

where
- VPAI = Periodic volume increment per acre (m^2/ha/yr)
- DBH = Diameter at breast height (cm)
- CR = Crown ratio
- BAL = Basal area in larger trees (m^2/ha)
- SI = 50 yr site index (m) (Bruce 1981)
- BAtotal = Basal area, all species (m^2/ha)
- CUTBA = CUT basal area, all species (m^2/ha)
- FOLRET = Current average foliage retention for the plot (yrs)
- THIN = 1 if plot was thinned, 0 if not
- TLD = Interaction term: THIN*ln(dbh)
- TBAL = Interaction term: THIN*ln(dbh)
- TFLD = Interaction term: THIN*FOLRET*ln(dbh)
- CFLD = Interaction term: Control*FOLRET*ln(dbh)

Parameter estimates (Table 5) indicated that periodic annual volume increment increased with increasing diameter, crown ratio, site index, and foliage retention, and decreased with increasing total basal area, basal area removed, and thinning. The positive values of the TLD and TBAL interaction terms reflect the increased growth response, by tree size and position, of similarly sized trees in the treated plots, after accounting for the negative of effect of thinning. The TFLD and CFLD interaction terms reflect the differential volume growth response, by tree size, to thinning at different levels of foliage retention. The interactive effect of foliage retention and tree size is shown in figure 6.

Table 5. Parameter estimates for individual tree model describing periodic annual volume increment (equation[4]).

Variable	Parameter Estimate	Standard Error
d_0	-14.31487	1.02052
d_1	2.74044	0.13905
d_2	0.42064	0.06920
d_3	-0.00885	0.00190
d_4	1.74890	0.25701
d_5	-0.92307	0.13666
d_6	-0.01777	0.00331
d_7	0.47272	0.16809
d_8	-1.29389	0.44758
d_9	0.21509	0.12800
d_{10}	-0.01103	0.00351
d_{11}	-0.08527	0.04673
d_{11}	-0.09915	0.04660

As should be expected from the plot-level regression, trees of any size in thinned stands are growing less than similarly sized trees in unthinned stands. Furthermore, as diameters decrease, trees in stands of low foliage retention grow at a diminishing percentage of similarly sized healthy trees. Put another way, larger diameter trees maintain a higher percentage of their non-infected growth potential than smaller trees as foliage retentions decrease.

Discussion

A major weakness in the retrospective phase of this study was the unknown effect of thinning on foliage retention. Knowing the initial pre-treatment foliage retention has rectified this problem. While

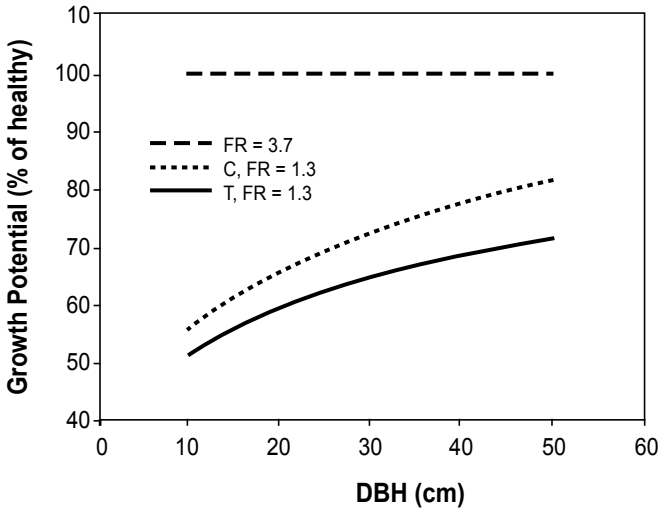

Figure 6. Growth potential of individual trees by diameter and foliage retention implied by model [4]

the analysis indicates that there is a significant treatment effect of thinning on foliage retention and that it depends on the initial foliage retention, it is small, amounting to a maximum average negative effect of 0.13 years even at the lowest retention levels.

The change in crown sparseness also shows a significant treatment effect, otherwise depending on average crown ratio, and the amount of basal area removed. On average, both control and treatment plots experienced an increase in crown sparseness. At the dataset mean crown ratio of 0.51, the equation implies that when less than 10.6 m^2/ha (46 ft^2/ac) of basal area per acre is removed, CL:SA decreases with treatment. When less than 15.3 m^2/ha (66 ft^2/ac) of basal area per acre is removed, CL:SA goes down relative to the controls. Although this suggests that crowns densify slightly when very little basal area is removed, this result may be an artifact of crown retention (or loss) during harvest. Trees in heavily thinned stands are more likely to end up with one-sided crowns, thereby increasing CL:SA by chainsaw effect. It is difficult to know whether changes in CL:SA are driven more by crown recession or needle loss.

The previous phase of this study indicated that at a foliage retention of 1.65 years and a crown sparseness of 13 cm/cm^2, a stand thinned 4-10 years previous would be producing an average of 30% less volume than an uninfected stand with a foliage retention of 3.65 years and a crown sparseness of 7 cm/cm^2. The implied volume loss from using these values of foliage retention in equation [3] is 32%. The similarity of these values underscores the relative stability of foliage retentions before thinning and two years later.

Although both foliage retention and crown sparseness have proven significant estimators in previous models describing growth declines in SNC infected stands (Maguire and Kanaskie 2002; Maguire et al. 2002), crown sparseness was not retained in equation [3]. Inclusion of crown sparseness with foliage retention was found to make both only marginally significant. Furthermore, the variability of crown sparseness between plots was relatively low. Mean crown sparseness of plots was 5.9 cm/cm^2 with a standard deviation of 1.6 cm/cm^2. If the one plot in the Cascades isn't used, these values are 5.55 and 1.25 cm/cm^2.

A major difference between this study and the retrospective study (Mainwaring et al. 2003) was the sampling procedure used for collecting crown sparseness data. This study used 5-10 dominant/co-dominants per plot, whereas the retrospective study used 40 trees (including 10 doms/co-doms) ranging across the diameter distribution. Mean and standard deviation of crown sparseness for the retrospective study was 8.9 and 2.7 cm/cm^2. When dataset averages for the retrospective plots was limited to the 10 trees with the largest dbh per plot, mean and standard deviation was 5.4 and 1.3 cm/cm^2. It may be that dominant trees are less indicative of a stand's average tree crown density than that calculated from a range of size classes.

With growth losses accumulating since 1990 (Maguire et al. 2002), dominants in stands this age are likely to be those trees that are most tolerant of SNC. Previous work in the genetic heritability of SNC symptom expression suggests that crown density is the best foliage indicator for judging SNC tolerance, but that the best single trait to select for would be

basal area increment (Johnson 2002). The fact that dominant trees have approximately similar CL: SA's, (and thus crown densities) over a large range of infection intensities, suggests that any silvicultural treatment that increases the proportion of these trees within a stand will have a positive effect on stand growth per unit of basal area. If trees of all sizes had equal tolerance to SNC, it might be expected that trees in the lower crown classes would grow better in relation to their counterparts in healthy stands as infection levels increased because of less light interception by the sparser-crowned dominants. However, the individual tree analysis suggests that this is not the case (figure 6). Thinning from below, the standard practice in state forests, removes stems that have grown slower due to genetics, microsite, quality of planting, and other factors. In coastal forests, Swiss needle cast imposes further variation.

Younger stands have shown much higher growth losses than is estimated for these older stands. Unthinned 10-30 year old stands with foliage retention as low as 1.3 years have shown growth losses between 40 and 45% (Maguire et al. 2002). In contrast, equation [3] implies growth losses of about 17% for unthinned older stands at similar levels of SNC. The younger stands have undergone much less SNC-influenced differentiation, and the canopy is more equitably shared between trees growing well with SNC and those that are not. In the older age classes represented in this study, the more highly differentiated stands are probably stocked with a larger component of trees that show some SNC tolerance. This may help to explain the negative correlation of RD with volume growth. Besides accounting for non-Douglas-fir competitors, a higher RD for a given basal area indicates a stands made up of more, but smaller trees. A stand with fewer and larger trees probably contains a higher percentage of tolerant trees. This is not to say that a stand can be thinned into tolerance, but it may explain why growth losses appear to decrease with stand age.

The reduction in volume growth with treatment at all levels of SNC, revealed by the randomized block ANOVA without covariates, is expected. Even accounting for a positive thinning response from individual trees, stand volume growth declines due to a reduction in growing stock (Marshall and Curtis 2001). More significant, the difference in volume growth loss between thinned and unthinned SNC-infected stands and their respective healthy counterparts increases as foliage retention drops. The minimal changes in foliage retention and crown sparseness suggests that it can probably be attributed to the rate at which trees are able to capture unclaimed site resources and respond to increased growing space. In an unthinned stand of commercial thinning age, a trees ability to capture site resources is limited by its immediate neighbors—crown expansion through height growth is negated to various degrees by crown recession through shading, and belowground resources are shared in a common, though localized pool. As a result, even dominant trees are limited in their growth, whether the stand is healthy or not. Thinning provides more space, and hence, more resources to trees, but their ability to increase their growth by accessing these resources depends on their ability to grow into or capture them. Aboveground expansion, through height and branch growth, has been found to slow with SNC infection intensity (Maguire et al. 2002, Mainwaring et al. 2002). Nothing is known about how SNC affects belowground expansion. A residual tree with fewer neighbors laying claim to its groundwater can use it for growth, but only if its plumbing can take advantage of the increase. Experiments have found that SNC infected trees show a declined water transport capacity at the tree, branch and root levels (Manter 2002). Heavily infected stands that have been thinned are thus less able to match the accelerated growth of uninfected thinned stands. In contrast, heavily infected unthinned stands have a slower-growing basis of comparison.

It should be remembered that these are two-year results. Two-year growth of just-thinned stands without SNC doesn't reflect the full growth potential gained from thinning. This is mostly due to the time needed to develop more crown, and, on poorer sites, to so-called thinning shock (Harrington and Reukema 1983, DeBell et al. 2002). Results from the retrospective study, based on 4 to 10 years of growth following thinning, indicate similar levels of growth loss (~35%) when comparing the most heavily infected stands to unin-

fected thinned stands. Because the individual trees of the uninfected stands are accelerating in growth in response to their spacing, the fact that growth loss in the worst stands at 2 years and up to 10 years is approximately equal indicates that they also are accelerating in growth. This fact has been confirmed by examining the annual ring growth from the trees of the retrospective dataset.

In this dataset, unthinned, yet heavily infected stands are maintaining good absolute growth. The control plot with the lowest growth is Sam Downs, with 10.92 m^3/ha/yr (156 ft^3/acre/year) (table 1). The four unthinned stands with the lowest foliage retention (average: 1.48 years) produced 13.0 m^3/ha/yr (185.8 ft^3/ac/yr). Average cubic volume growth for the 10 most heavily infected plots (average foliage retention =1.76 yrs) is 14.98 m^3/ha/yr (214 ft^3/ac/year), which, with trees this size, is about 1000 board feet/acre/year. Although the growth of heavily infected thinned plots is significantly lower, the average worst case scenario of ~35% cubic volume growth loss still provides a better economic return than western hemlock. In fact, given current management regimes and log prices, simple economic analysis suggests that Douglas-fir provides a better return than western hemlock until cubic volume growth loss approaches 50%.

Two of the shortcomings in this remeasurement of the first 15 permanent plots will be addressed with next year's measurement of the second set of 15. First, next year's set includes 3 plots on the Elliot forest of the Coos district, expanding the range of inference. Second, this set did not have many plots in the moderate infection range—between 2 and 3 years of foliage retention. Six of the 15 plots from next year do include this range, thus providing a better coverage of initial infection intensity.

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Influence of Swiss Needle Cast on Douglas-fir Stem Properties

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Introduction

Stem properties such as shape, heartwood formation rate, and juvenile wood core size are strongly controlled by the development of the crown. Quantitative relationships between stem taper and crown size and condition have not been explicitly developed, while other stem properties have not been thoroughly examined across a range of stand conditions in this region. Swiss needle cast (SNC) provides an interesting opportunity to begin trying to model the relationship between crown development and stem properties as the disease influences both crown size and condition.

Previous work on the impact of SNC on stem properties indicates that the disease leads to significantly narrower sapwood, narrower growth rings, lower sapwood moisture content, higher overall wood density, and narrower tracheid cell wall thickness than normal (Johnson et al. 2003). In addition, Gartner et al. (2003) indicated that the modulus of elasticity (MOE) and modulus of rupture (MOR) were higher in stands impacted by SNC, but there was no association between these variables and the needle retention of individual trees. However, a primary conclusion of their research was that results reported in the literature on growth rate effects on Douglas-fir wood properties are inconsistent and call for further research in the area. Furthermore, the conclusions from these studies were based on samples taken only at breast height and crown base, which may not represent all the changes occurring throughout the stem.

The objectives of this study were, therefore, to determine and model the influence of SNC on several stem properties such as (a) shape and taper, (b) vertical distribution of annual increment, (c) heartwood formation rates, (d) sapwood volume, (e) size of the juvenile wood core, and (f) bark thickness and cross-sectional area. It is believed SNC will have a significant impact on each of these properties largely because of the disease's influence on crown size and condition.

Methods

Field and lab work

During the spring of 2002 and winter of 2004, 105 trees were destructively sampled and sectioned for stem analysis. Three to four trees per stand and ten to fifteen discs per tree were sampled. The 31 plots were a subsample of those from both the growth impact (Maguire et al. 2002) and commercial thinning (Mainwaring et al. 2003) studies (Table 1).

In the field, each disc was measured for diameter outside bark (dob), diameter inside bark (dib), and heartwood diameter (hw) along the longest and shortest axes. A subsample of trees were selected for intensive stem analysis and the discs were brought back to the laboratory. Annual increment for the past five growing seasons, the number of rings in both the sapwood and heartwood, and diameter of the juvenile wood core were measured on four axes. The juvenile wood core in this study was defined as the first 15 rings from the pith as it is the mid-value for the range of typical juvenile transition ages for second-growth Douglas-fir as suggested in Gartner et al. (2002). A total of 1,386 and 311 discs were measured in the field and laboratory, respectively.

Data analysis

Bark cross-sectional area, stem shape, vertical distribution of annual increment, sapwood volume, and size of the juvenile wood core were analyzed by first fitting a variable exponent taper model to assess the effects of SNC on each of these variables. The models were each fitted with multi-level random effects and a specified error structure to account for the hierarchical nature of the data and to reduce autocorrelation between observations. The resulting equation was then numerically integrated to estimate total volume for the stem and these values were regressed on other stand variables and foliage retention.

Influence of SNC on bark thickness was determined in a similar manner: a general model was fit to each plot and the final parameter estimates were regressed on other stand variables. The general model form was:

$$[1]\quad dib = \beta_{11} DBH^{\beta 12} + \varepsilon_1$$

where dib is diameter inside bark (cm), dob is diameter at breast height (cm), the β_i's are parameters to be estimated for each plot from the data, and $\varepsilon_i^{iid} \sim N(0, \sigma_1^2)$.

Similarly, the formation rate of heartwood was analyzed by fitting a general model to each plot and regressing the final parameter estimates on stand variables. The general model was a linear function between the number of heartwood rings and cambial age, having the following form:,

$$[2]\quad HW_{rings} = \beta_{20} + \beta_{22} CA^2 + \varepsilon_2$$

where HW_{rings} is the number of heartwood rings, CA is cambial age, the β_i's are parameters to be estimated for each plot from the data, and $\varepsilon_i^{iid} \sim N(0, \sigma_1^2)$ (Björklund 1999; Pinto 2004). The slope of this equation indicates the number of heartwood rings that are formed each year.

Table 1. Stand and tree attributes of stems selected for analysis.

Variable	***MEAN***	***STD***	***MIN***	MAX
STAND				
Site index	38.99	23.08	27.70	47.44
Age	31.82	15.11	11.00	62.43
Stems per ha	752.49	673.82	175.00	4408.95
Relative density (Curtis 1982)	8.14	4.02	3.09	18.49
Douglas-fir basal area (m^2/ha)	39.29	23.08	9.97	104.28
Douglas-fir QMD (cm)	31.71	10.67	11.41	53.59
Foliage retention	2.42	0.85	1.20	4.38
Distance from coast (km)	19.48	12.74	1.07	53.00
Crown sparseness index	5.34	1.66	1.64	9.67
Tree				
DBH (cm)	32.48	11.05	12.50	66.6
HT (m)	25.49	8.38	11.90	45.80
CL (m)	14.31	3.84	6.96	27.20
RHT	0.92	0.11	0.66	0.99
Crown sparseness index	6.99	3.86	2.15	34.94

Table 2. Equations forms, R^2, and root mean square errors (RMSE) for models presented in this study.

Equation	*Model Form*	*R^2*	RMSE
1a; bark thickness	$dib = 0.9445842 * DBH \wedge 0.9955156$	0.99	0.11
1b; bark thickness by plot	$_{11} = 0.8541 + 0.0054 * QMD_{DF}$ $_{12} = 1.019067 - 0.00151 * QMD_{DF}$	0.31	0.04
1c; bark cross-sectional area	$bca = 4004.0 * BACR^{1.1860} \frac{1-\sqrt{Z}}{1-\sqrt{\frac{1.37}{HT}}}^{8.2227*Z-5.8348*\sqrt{Z}+2.9219*\frac{DBH}{HT}+0.04531*CL-0.0510*HCB-0.1275*FOLRET-3.4979*(\frac{DBH}{HT}*Z)}$		91.97
2; heartwood formation	$HW_{rate} = 2.6684 - 0.1037 * SI + 0.7987 * PBADF + 0.4058 * \log(TPH_{DF}) - 0.9914 * N - 0.3812 * FOLRET + 0.2416 * (FOLRET*N)$	0.98	0.07
3a; stem taper	$dib = 0.9446 * DBH^{0.9955} \frac{1-\sqrt{Z}}{1-\sqrt{\frac{1.37}{HT}}}^{-0.6962*Z^2-1.8042*\sqrt{Z}+1.3605*Exp(Z)-0.0052*DBH-0.1358*FOLRET}$	0.98	0.83
3b; volume bias	$VOL_{BIAS} = -166.4094 + 13.5384*TOPHT-6.2135*QMD_{DF}-6.5662*CLSA_{STAND}+31.8581*FOLRET$	0.82	28.75
4; vertical distribution of increment	$bai = \exp(-6.3161 + 1.4022 * \log(DBH + 1) + 1.6052 * \log(SI - 1.37) + 0.9428 * \log(\frac{CR + 0.2}{1.2}) - 0.1189 * \sqrt{BA_{DF}} + 0.1310 * FOLRET - 0.0512 * CLSA) * \frac{1-\sqrt{Z}}{1-\sqrt{\frac{1.37}{HT}}}^{4.5269*Z+5.0869*\sqrt{Z}\ 0.6229*\frac{DBH}{HT}-0.0329*CLSA-0.0003*SDI+0.7936*CR}$	0.56	10.24
5; sapwood taper (known $sap_{BH)}$	$sap = sap_{BH} \frac{1-\sqrt{Z}}{1-\sqrt{\frac{1.37}{HT}}}^{9.3324*Z-8.4537*\sqrt{Z}+1.3877*\frac{DBH}{HT}-0.0473*CL+2.8759*CR+0.04123*HCB-2.0074*(\frac{DBH}{HT}*Z)-0.0696*FOLRET}$	0.74	9.22
5; sapwood taper (predicted SAP_{BH})	$sap = (4.5961 * DBH^{1.2127}) * \frac{1-\sqrt{Z}}{1-\sqrt{\frac{1.37}{HT}}}^{9.4116*Z-8.2971*\sqrt{Z}+1.4566*\frac{DBH}{HT}-0.04347*CL+2.6885*CR+0.03719*HCB-2.1262*(\frac{DBH}{HT}*Z)-0.1054*FOLRET}$	0.79	7.98
6; juvenile wood taper	$juv = (0.9446 * DBH^{0.9955}) * [(1 - \exp(-2.8036 * CR)]^{(1.4526*(DBH/HT))} \frac{1-\sqrt{Z}}{1-\sqrt{\frac{1.37}{HT}}}^{2.4474*Z-2.3062*\sqrt{Z}+2.3924*CR+0.0783*\sqrt{BADF}-0.0482*SI+0.0449*HCB+0.0284*CLSA}$	0.55	6.71
7; stand volumes	$\log(VOL) = 3.3346 + 0.0406*TOPHT - 0.0014*TPH_{DF} + 0.2503*RD_{DF} + 0.06285*COSA + 0.0383*FOLRET$ $\log(SAPVOL) = 3.5799 + 0.0241*TOPHT - 0.0014*TPH_{DF} + 0.2388*RD_{DF} + 0.0808*FOLRET$ $\log(JUVVOL) = 3.1776 - 0.00159*TPH_{DF} + 0.2274*RD_{DF} + 0.0848*COSA + 0.0330*SI$ $\log(CAIVOL) = -1.2077 + 0.0276*TOPHT - 0.0006 * TPH_{DF} + 0.1471*RD_{DF} + 0.0516*SI + 0.1443*FOLRET$ $\log(BVVOL) = 1.4114 + 0.0358*TOPHT - 0.0014*TPH_{DF} + 0.2491*RD_{DF} + 0.1127*FOLRET$	0.95	0.20

Results

Bark thickness and cross-sectional area

Foliage retention (FOLRET) did not influence bark thickness. Bark thickness only showed a positive relationship with increasing Douglas-fir stand quadratic mean diameter. Doubling Douglas-fir stand quadratic mean diameter (QMD_{DF}) only increases mean bark thickness by 1.4%. A general bark thickness equation was, therefore, used in the stem taper equation.

Foliage retention, however, had a significant influence (p=0.0001) on bark cross-sectional area throughout the stem after accounting for basal area times a modified live crown ratio (BACR), Z (relative height in the stem), square root of Z, DBH/HT, DBH/HT*Z, CL (crown length), and CR (crown ratio). On average, the bark cross-sectional area was 32.3% greater at a given height for an average-sized tree in a stand with one year of foliage retention compared to the same sized tree in a stand with 4 years of retention (Figure 1). In an average stand with one year of foliage retention, total bark volume has been reduced by 9.9% when compared to an average stand with four years of retention after accounting for stand top height (TOPHT), Douglas-fir stems per ha (TPH_{DF}), and Douglas-fir relative density (RD_{DF}).

Heartwood formation rate

Mean heartwood formation was 0.83 rings per year and varied from 0.01 to 1.31 rings per year. The rate of formation was positively correlated with TPH_{DF}, percent basal area in Douglas-fir (PBADF), and southern aspect, while it decreased with improved site index (SI) and FOLRET. The effect of foliage retention, however, depended on aspect as indicated by the significance of their interaction. The mean heartwood formation rate is 51.9 to 73.5% greater in stands with high SNC compared to a healthy stand depending on aspect. In an average stand with a southern aspect and a foliage retention of one year, the heartwood formation rate formation rate is expected to be 1.56 rings per year.

Stem taper and volume

Foliage retention had a significant effect on stem taper (p=0.0207) after accounting for DBH and several transformations of Z. The model had a R^2 of 0.95 and a likelihood ratio test also suggested that inclusion of foliage retention significantly improved model fit (p<0.0001). For a given DBH and relative height, a reduction of foliage retention significantly reduced DIB throughout the stem, except below breast height (Figure 2).

Mean stand volume losses due to SNC were estimated to be 17.5% after accounting for TOPHT, TPH_{DF}, the cosine transformation of aspect (COSA) and RD_{DF}. A significant difference between stand volumes estimated using this stem taper equation and those estimated using Bruce and DeMars' (1974) equation existed. This bias increased with greater TOPHT and foliage retention, while it decreased with QMD_{DF} and plot mean crown sparseness index ($CLSA_{Stand}$). Mean bias was 18.68 m^2 ha^{-1} and ranged from -38.21 to 244.55 m^2 ha^{-1}.

Vertical distribution of annual increment

Foliage retention had a significant effect on the absolute amount of annual increment (p=0.0061), but not the relative amount of annual increment. The crown sparseness index, however, had

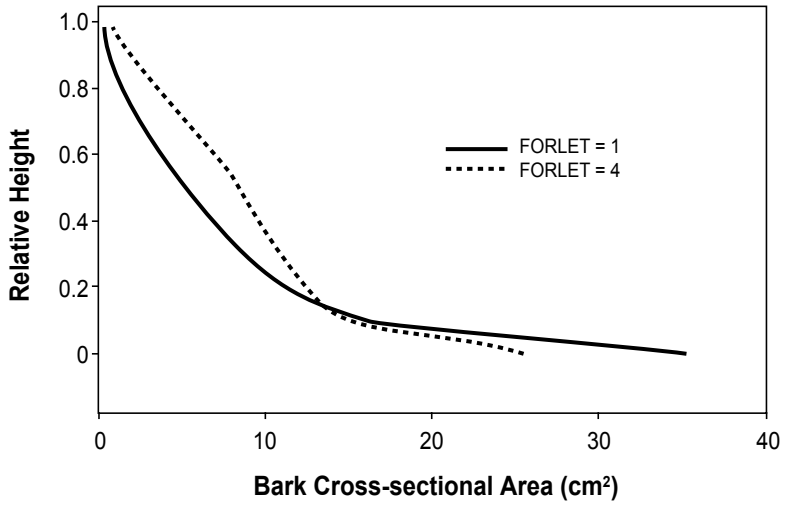

Figure 1. Predicted bark cross-sectional area profile for an average sized tree (DBH = 31.7 cm, HT = 24.8 m, HCB = 12.2 m) in a stand with one (solid line) and four (dashed line) years of foliage retention.

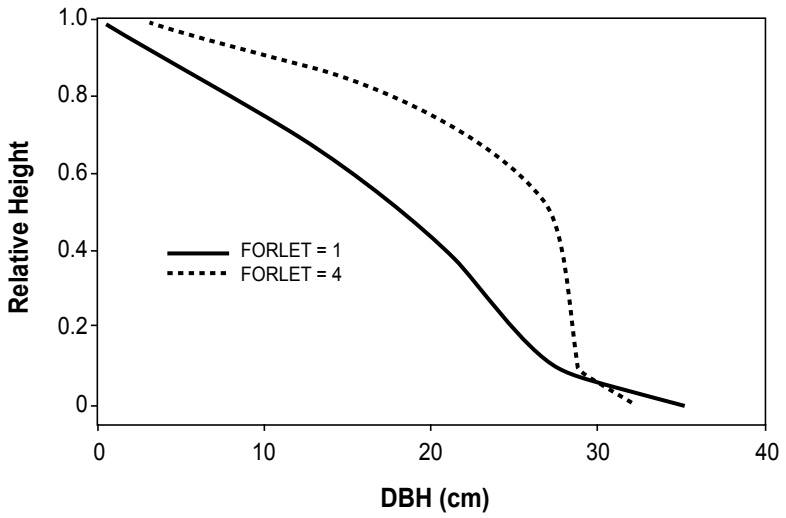

Figure 2. Predicted stem profile for an average sized tree (DBH = 31.7 cm, HT = 24.8 m, HCB = 12.2 m) in a stand with one (solid line) and four (dashed line) years of foliage retention.

a significant effect on both the absolute ($p<0.0001$) and relative ($p=0.007$) amount of annual increment. The absolute amount of annual increment at breast height also showed a significant relationship with DBH, SI, crown ratio (CR), and stand basal area in Douglas-fir (BA_{DF}). The vertical distribution of annual increment was related to Z, the square root transformation of Z, DBH/HT, CR, and the stand density index (SDI; Reinke).

At breast height, current basal area growth was reduced by 40.5% for an average-sized tree in a stand with one year of foliage retention when compared to a similar tree in a stand with four year of foliage retention. Annual basal increment was also significantly reduced by an average of 33.5% throughout a stem located in a stand with high SNC compared to one with low SNC, except in the upper 20% of the stem where the mean reduction was 8.9% (Figure 3). Mean current annual increment (CAI) was estimated to be reduced by 35.8% in a stand with one year of foliage retention when compared to a stand with four years of foliage retention after accounting for TOPHT, TPH_{DF}, RD_{DF}, and SI.

Sapwood taper and volume

Foliage retention had a significant effect on sapwood taper ($p=0.0324$) after accounting for Z, the square root of Z, DBH/HT, crown length, CR, height to crown base (HCB), and the interaction between DBH/HT and Z. Mean stand sapwood volume losses due to a reduction in foliage retention from 4 to 1 were estimated to be 21.9% after accounting for

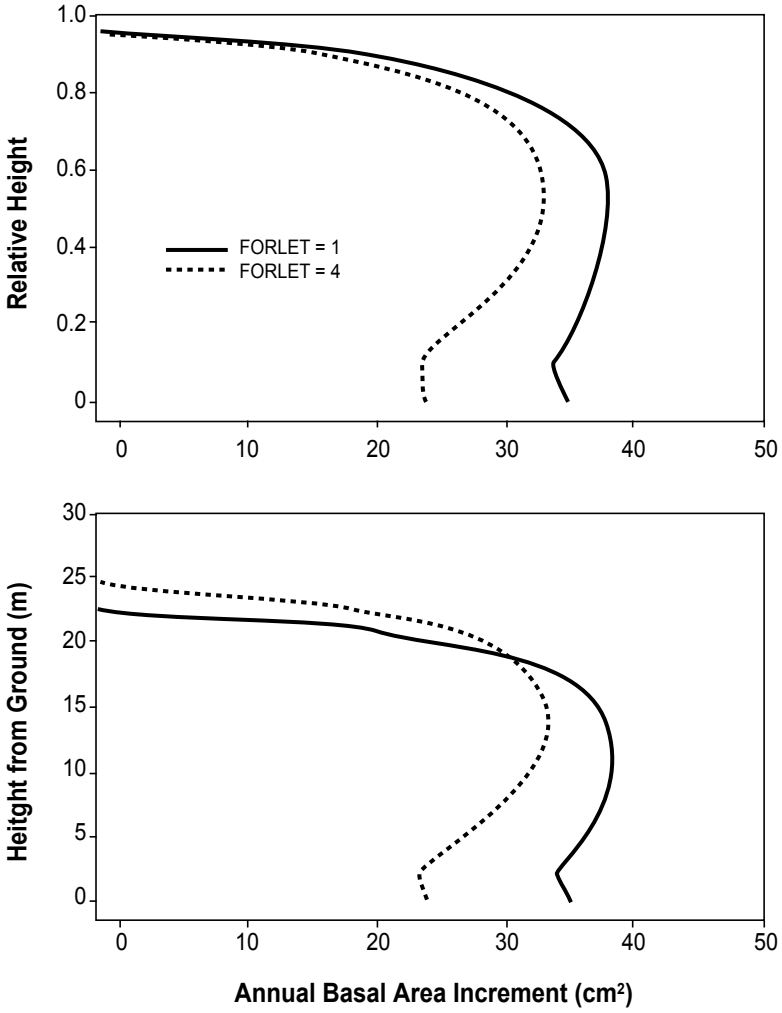

Figure 3. Predicted profile of annual basal area increment (cm^2) for an average-sized tree (DBH = 31.7 cm, HT = 24.8 m, HCB = 12.2 m, SDI = 714.8, SI = 39.5 m, BA_{DF} = 31.9 m^2 ha^{-1}) on a plantation with one (solid line; CLSA = 8.0) and four (dashed line; CLSA = 5.3) years of foliage retention over relative (top) and absolute (bottom) stem height.

TOPHT, TPH_{DF}, and RD_{DF}. For a given DBH/HT, CL, CR, HCB, and Z, a reduction of foliage retention significantly reduced sapwood area throughout the stem, except below breast height (Figure 4).

Juvenile wood core taper and volume

Foliage retention did not have a significant effect on the taper of the juvenile wood core, while the crown sparseness index did show a significant relationship (p=0.0001) with it after accounting for Z, the square root of Z, DBH/HT, CR, SI, HCB, and basal area of Douglas-fir (BA_{DF}). The juvenile wood core profiles of trees with differing crown sparseness indices were similar for nearly 60% of the stem (Figure 5). For a healthy 30-yr plantation, an estimated 78.1% of its volume is in juvenile wood, which can range from 70.6 to 85.5% of stand volume depending on SNC severity.

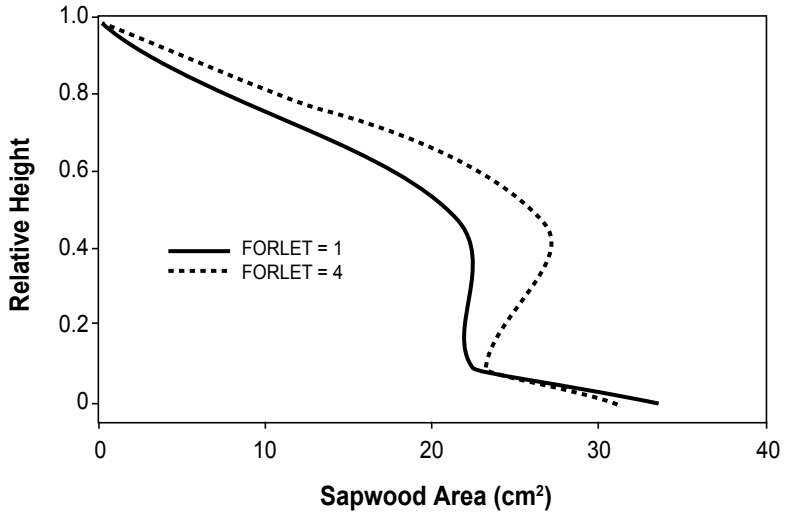

Figure 4. Predicted sapwood profile for an average sized tree (DBH = 31.7 cm, HT = 24.8 m, HCB = 12.2 m) in a stand with one (solid line) and four (dashed line) years of foliage retention.

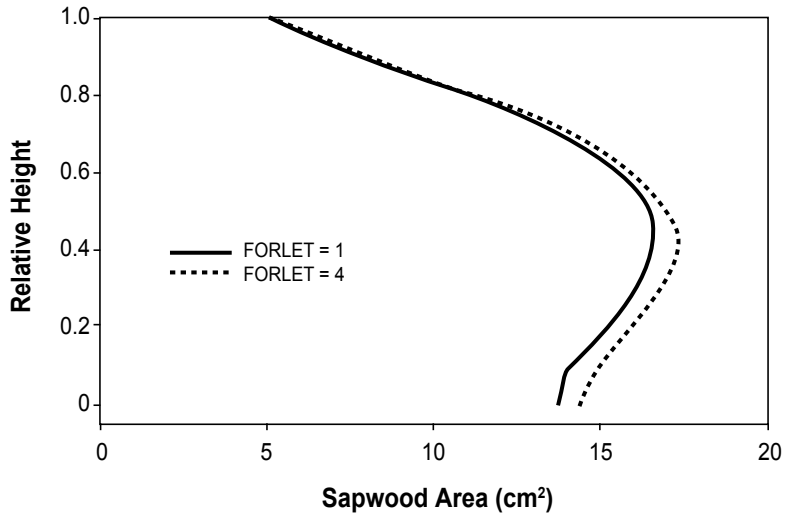

Figure 5. Predicted juvenile wood core profile for an average-sized tree (DBH = 31.7 cm, HT = 24.8 m, HCB = 12.2 m) in with a crown sparseness index (CLSA) of 7.98 (solid line) and 5.28 (dashed line).

Discussion

Alterations in both the size and vigor of the crown have led to significant changes in the stem, particularly bark cross-sectional area, heartwood formation rates, stem taper, and the vertical distribution of annual increment. Surprisingly, SNC had little impact on bark thickness and the juvenile wood core size. Similarly, Brack et al. (1985) found bark thickness to be highly correlated with other variables, while bark cross-sectional area was closely related with several physiological variables such as leaf area and crown condition. The finding that foliage retention influences bark cross-sectional area throughout the stem agrees with this prior conclusion.

In terms of juvenile wood, Fabris (2000) generally found that the larger the volume of crown foliage relative to length of branch-free stem, the lower the passage from juvenile wood to mature wood below the base of the live crown, resulting in a greater proportion of juvenile wood. In addition, when crown ratio was held constant, the juvenile wood core profile was mostly cylindrical with the faster growing trees showing greater tapering toward the stump (Fabris 2000). It was believed that the significant reduction in leaf area caused by SNC and the resultant slower stem growth would alter the juvenile wood core profile in this study, which appeared not to be the case. This, however, may be an artifact of the method

used to reconstruct the juvenile wood core in this study as a constant transition age of 15 years was assumed, while the profiles obtained by Fabris (2000) were developed from actual transition ages. Fifteen years is similar to the value reported for Douglas-fir by Wellwood and Smith (1962), but five years lower than most other studies (Fabris 2000).

The reductions in mean basal area growth were similar to those reported in Maguire et al. (2002). The reduction in volume growth due to SNC, however, was found to be much lower than the 52% reported in that study (Maguire et al. 2002). This may be to the alteration in stem shape caused by the disease, annual weather fluctuations, and changes in SNC severity. Similar vertical profiles of annual increment is also surprising given the significant within-crown modifications imposed by SNC. A profile comparable to the vertical distribution of leaf mass presented in Weiskittel (2004) would be expected, which suggests a possible nonlinear relationship between leaf mass and annual increment.

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