Swiss Needle Cast Cooperative

Annual Report 2005

OSU
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Swiss Needle Cast Cooperative

Edited by Doug Mainwaring and David Shaw

Layout by Gretchen Bracher, FCG

Income Sources and Expenditures, 2005

Income	
Membership dues	$115,000
Oregon State Legislature	$120,000
Total Income	**$235,000**
Expenditures (Projects):	
Salaries and Wages:	$ 80,118
Supplies and Services	$ 97,919
Travel	$ 1,500
Indirect costs	$ 23,289
Total expenditures	**$202,826**
Net total	**$ 32,174**

Contents

To: SNCC Members
From: David Shaw
Date: October 2005
Subject: 2005 Annual Report

Special thanks go to Doug Mainwaring for his work over the past year serving as Acting Director of the Coop. Doug has done a really good job getting the books in order, overseeing two Annual Reports, and keeping everyone informed and involved. He will be stepping down in mid November, 2005. With this 2005 Annual Report David Shaw will be assuming the Directorship of the Swiss Needle Cast Cooperative.

I would like to also thank Greg Filip for all the work he has done over the years as Director of the SNCC, as well as the large number of scientists that have done the amazing work accomplished by the coop.

This past November 16, 2004 the SNCC sponsored a day long conference entitled, "Growing Douglas-fir in the Swiss Needle Cast Zone". Thirteen presentations were given by researchers and cooperators that summarized our current knowledge of the SNC outbreak in the Coast Range, the biology of the causal agent (*Phaeocryptopus gaeumannii*), the impacts of SNC on Douglas-fir trees and plantations, silvicultural tools to deal with the disease, and the economics of managing Douglas-fir in the coast range, as well as some perspective from New Zealand where an SNC outbreak predated our own. This conference was an example of the efforts of the SNCC to produce scientific knowledge and get that information to users. Thanks to all the presenters and participants.

The current budget picture for the SNCC provides us with the capacity to continue to fund the Oregon Department of Forestry SNC survey and monitoring program, as well as maintain the growth impact study. The State of Oregon has contributed additional dollars for the biennium 2005-2007 which will allow the coop to fund research. The current research program will be decided at our next Annual Meeting scheduled for January 25, 2006. Our Annual Meeting has been delayed from its traditional November date until January to accommodate schedules of some important cooperators. The January meeting will include a summary of current research, as well as presentations from scientists seeking funding from the cooperative. Decisions will be made on that date regarding which projects will be funded, making this Annual Meeting especially important.

I look forward to working with the SNCC members in making this cooperative a responsive and productive one.

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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.

List of Refereed Publications

2000

Hansen, E.M., Stone, J.K., Capitano, B.R., Rosso, P., Sutton W., Winton L., Kanaskie A., and M.G. McWilliams. 2000. Incidence and impact of Swiss needle cast in forest plantations of Douglas-fir in coastal Oregon. Plant Disease. 84: 773–779.

Manter, D.K., Bond, B.J., Kavanagh, K.L., Rosso, P.H., and G.M. Filip. 2000. Pseudothecia of Swiss needle cast fungus, Phaeocryptopus gaeumannii, physically block stomata of Douglas-fir, reducing CO_2 assimilation. New Phytologist 148: 481–491.

2001

Kastner, W., Dutton, S., and D. Roche. 2001. Effects of Swiss needle cast on three Douglas-fir seed sources on a low-elevation site in the northern Oregon Coast Range: Results after five growing seasons. West. Jour. of Ap. For. 16(1):31-34.

Manter, D. K., Kelsey, R. G., and J. K. Stone. 2001. Quantification of Phaeocryptopus gaeumannii colonization in Douglas-fir needles by ergosterol analysis. For. Path. 31: 229–240.

2002

Maguire D.A., Kanaskie A., Voelker W., Johnson R., and G. Johnson. 2002. Growth of young Douglas-fir plantations across a gradient in Swiss needle cast severity. West. Jour. of Ap. For. 17: 86–95.

Johnson, G.R. 2002. Genetic variation in tolerance of Douglas-fir to Swiss needle cast as assessed by symptom expression. Silv. Gen. 51: 80-86.

Maguire, D.A. and A. Kanaskie. 2002. The ratio of live crown length to sapwood area as a measure of crown sparseness. For. Sci. 48: 93-100.

Manter, D. K. 2002. Energy dissipation and photoinhibition in Douglas-fir needles with a fungal-mediated reduction in photosynthetic rates. J. Phytopathol. 150: 674–679.

Winton, L. M., Stone, J. K., Watrud, L. S., and E. M. Hansen. 2002. Simultaneous one-tube quantification of host and pathogen DNA with real-time polymerase chain reaction. Phytopathology. 92: 112–116.

2003

Johnson, G.R., Gartner, B.L., Maguire, D., and A. Kanaskie. 2003. Influence of Bravo fungicide applications on wood density and moisture content of Swiss needle cast affected Douglas-fir trees. For. Ecol. Man. 186: 339-348.

Manter, D.K., Bond, B.J., Kavanagh, K.L., Stone, J.K., and G.M. Filip. 2003. Modelling the impacts of the foliar pathogen, Phaeocryptopus gaeumannii, on Douglas-fir physiology: net canopy carbon assimilation, needle abscission and growth. Ecological Modeling. 164: 211–226.

Manter, D.K., and K.L. Kavanagh. 2003. Stomatal regulation in Douglas-fir following a fungal-mediated chronic reduction in leaf area. Trees : structure and function. 17:485-491.

Manter, D.K., Winton, L.M., Filip, G.M., and J. K. Stone. 2003. Assessment of Swiss Needle Cast Disease: Temporal and Spatial Investigations of Fungal Colonization and Symptom Severity. Phytopath-Z. 151:344-351.

Rosso, P. and E.M. Hansen. 2003. Predicting Swiss Needle Cast disease distribution and severity in young Douglas-fir plantations in coastal Oregon. Phytopathology 93: 790-798.

Winton, L.M., Manter, D.K., Stone, J.K., and E.M. Hansen. 2003. Comparison of biochemical, molecular and visual methods to quantify Phaeocryptopus gaeumannii. Douglas-fir foliage. Phytopathology. 93: 121–126.

2004

El-Hajj,-Z., Kavanagh,-K., Rose,-C., and Z. Kanaan-Atallah. 2004. Nitrogen and carbon dynamics of a foliar biotrophic fungal parasite in fertilized Douglas-fir. New Phytologist. 163: 139-147.

Grotta, A.T., Leichti, R.J., Gartner, B.L., and G.R. Johnson. 2004. Effect of growth ring orientation and placement of earlywood and latewood on MOE and MOR of very-small clear Douglas-fir beams. Wood and Fiber Science. 37: 207-212.

Kelsey, R.G., and D.K. Manter. 2004. Effect of Swiss needle cast on Douglas-fir stem ethanol and monoterpene concentrations, oleoresin flow, and host selection by the Douglas-fir beetle. For. Ecol. Man. 190: 241-253.

Temel, F., Johnson, G.R., and J.K. Stone. 2004. The relationship between Swiss needle cast symptom severity and level of Phaeocryptopus gaeumannii colonization in coastal Douglas-fir (Pseudotsuga menziesii var. menziesii). For. Path. 34: 383-394.

2005

Johnson, G.R., Grotta, A.T., Gartner, B.L., and G. Downes. 2005. Impact of the foliar pathogen Swiss needle cast on wood quality of Douglas-fir. Can. J. For. Res. 35: 331-339.

Mainwaring, D.B., Maguire, D.A., Kanaskie, A., and J. Brandt. 2005. Growth Responses to commercial thinning in Douglas-fir stands with varying intensity of Swiss needle cast. Can. J. For. Res. 35: 2394–2402.

Manter, D.K., Kavanagh, K. and C.L. Rose. 2005. Growth response of Douglas-fir seedlings to nitrogen fertilization: importance of Rubisco activation state and respiration rates. Tree Physiology 25: 1015–1021.

Manter, D.K., Reeser, P.W., and J.K. Stone. 2005. A climate-based model for predicting geographic variation in Swiss Needle Cast severity in the Oregon coast range. Phytopathology 95: 1256–1265.

Temel, F., Johnson, G.R., and W.T. Adams. 2005. Early genetic testing of coastal Douglas-fir for Swiss needle cast tolerance. Can. J. For. Res., 35: 521-529.

Swiss Needle Cast Aerial Surveys, 1996 to 2005

Alan Kanaskie, Mike McWilliams, Keith Sprengel, and 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 16 and ended on May 30, 2005, and covered approximately 2.09 million acres of forest. Approximately 500,000 acres in Eastern Tillamook, Lincoln, Lane and Douglas counties were not surveyed because of cloudy and rainy weather during May. In the 2005 survey we mapped 207,090 acres of Douglas-fir forest with obvious symptoms of Swiss needle cast; 128,483 acres north of the Lincoln-Lane county line, and 78,607 acres south of the Lincoln-Lane county line. Most of the increase occurred in Coos county and in the Newport-Eddyville area of Lincoln county. 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 2005. The survey maps for 1996 through 2005 appear in Figure 4.

The 2005 survey results end the trend of decreasing area with symptoms of Swiss needle cast. Even though the survey was truncated because of weather, we still mapped 30,000 more acres in 2005 than in 2004, a 17 percent increase. Had we been able to survey the entire area, it is estimated that the increase would have been approximately 60,000 acres (34 percent).

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 2005 survey was flown from May 21-30, which is relatively late in the target survey window. In general the survey was very challenging for observers because of poor

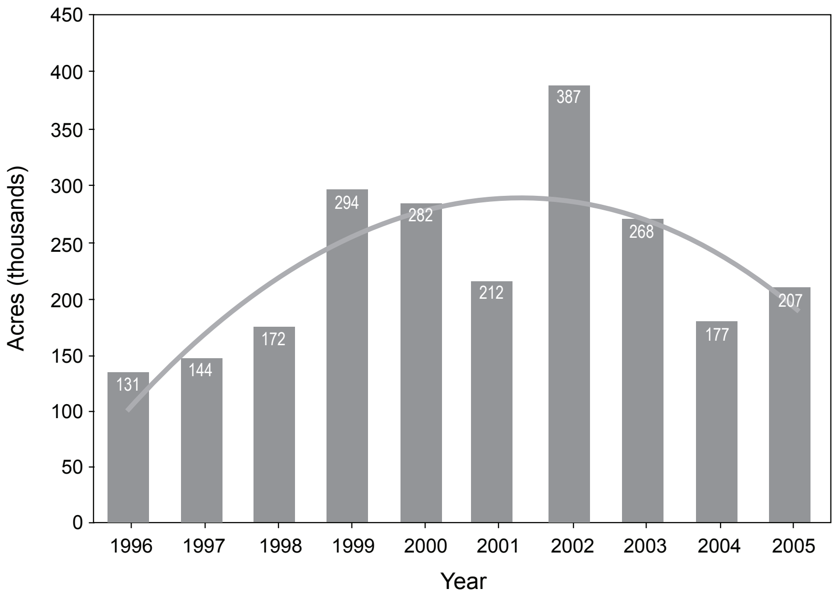

Figure 1. Trend in area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys in April and May, 1996-2005.

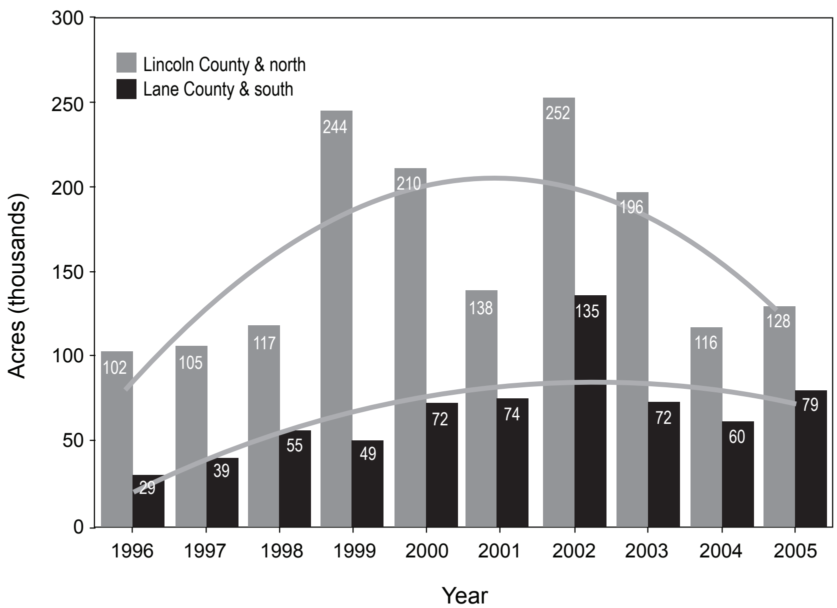

Figure 2. Area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys in April and May, by zone, 1996-2005.

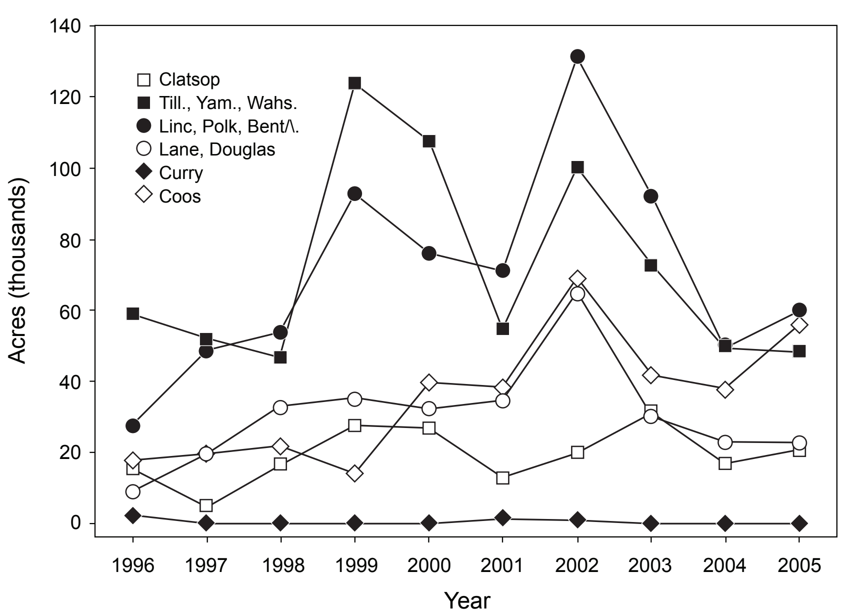

Figure 3. Area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys in April and May, by county group, 1996-2005.

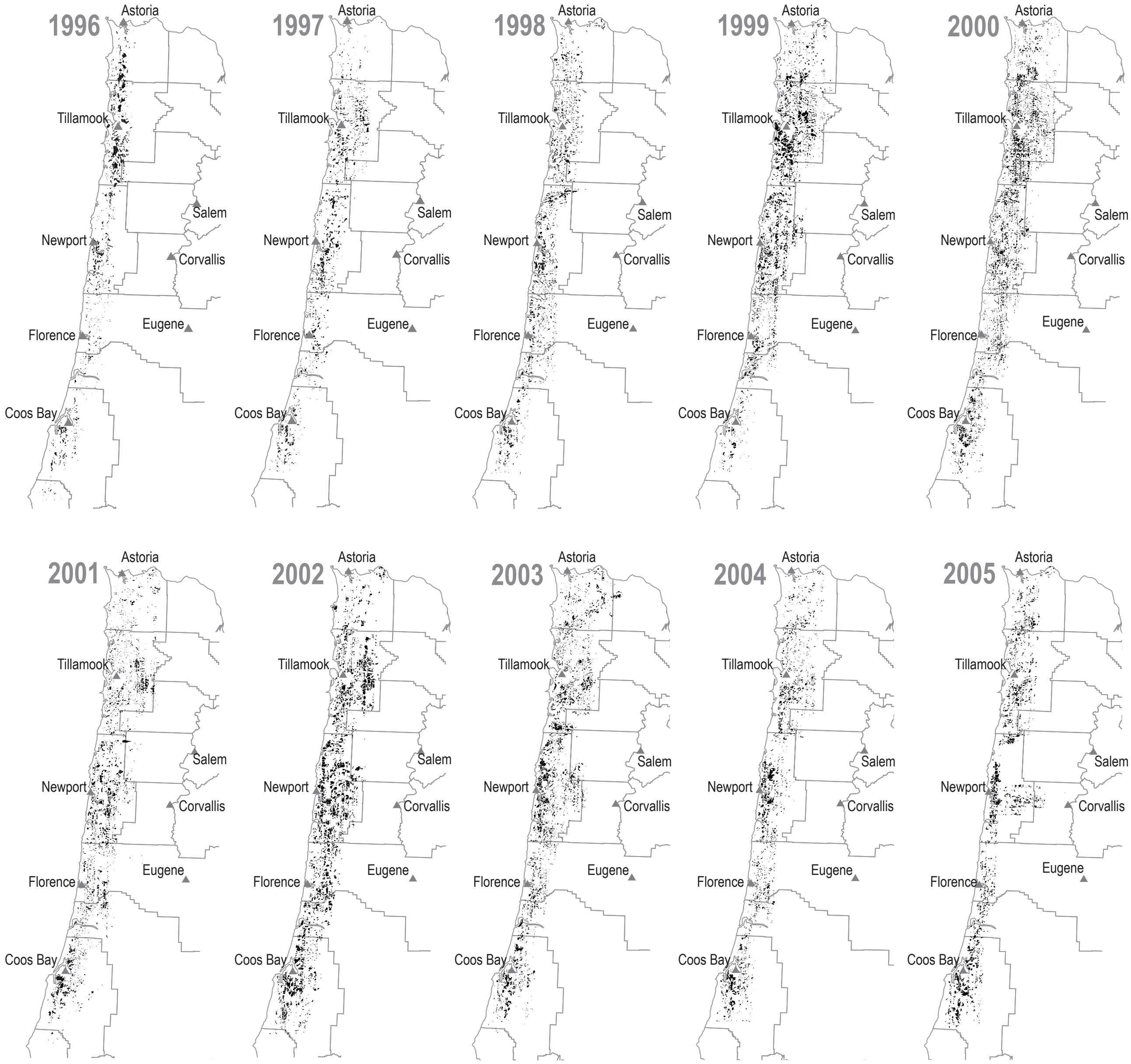

Figure 4. Areas of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial survey.

weather and early bud flush.

The Swiss needle cast aerial survey provides a conservative estimate of damage because observers can map only those areas where disease symptoms 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 that discoloration often is not severe 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, and coarsely documents trends in damage over time.

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 the Oregon Department of Forestry. Mike McWilliams (ODF) is the survey coordinator and primary aerial observer; Keith Sprengel (USFS), and Dave Overhulser (ODF) were additional aerial observers. Jim Baranek (ODF) piloted the plane.

Note:

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

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

Jeffrey Stone, Oregon State University, Gary Chastagner, Washington State University, and Alan Kanaskie, Oregon Department of Forestry

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 the study sites were 15-20 year old plantations that had been precommercially 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. A second pair of applications was made to the same plots in June 2003. Infection of one-year-old foliage sampled in 2003 and 2004 was reduced significantly for both years in all plot pairs. Infection levels remained lower for the foliage that received direct fungicide treatment (age classes 2002 and 2003), but infection levels were not significantly different between sulfur-treated and untreated plot pairs for the 2004 foliage cohort. While elemental sulfur was effective in reducing infection levels in new foliage, this effect appears to be relatively short-lived.

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 Green Diamond Resource Company (formerly Simpson Timber Co.), 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 each year. The first treatment was applied when at least 50% of new shoots were 1 – 3” expanded.

Foliage collection

Foliage was collected manually by climbing six 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. A collection of foliage was taken in fall 2002 after the first sulfur application for comparison of foliage elemental analysis. Subsequent collections were taken in early June 2003, late May, 2004, and early June 2005 for assessment of *P. gaeumannii* infection. Only one-year-old foliage was sampled in the 2003 and 2004 collections, three years of foliage was sampled in 2005 (age classes 2002, 2003, 2004) to assess residual fungicide effects.

Analyses

For assessment of infection by *P. gaeumannii*, foliage samples were collected in late May-early June, near the time of needle emergence, in 2003, 2004, and 2005. 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, 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).

Results

Phaeocryptopus gauemannii infection

Aerially applied sulfur fungicide significantly reduced infection in one-

Table 1. 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 comparison of infection index means (sulfur vs. check) for 2002 and 2003 foliage.

Site				
2002 Foliage	**Sulfur**	**Check**	**Difference**	**p**
Starker 10-yr-old	0.3	6.96	6.7	0.001
Starker 20-yr-old	0.1	12.16	12.1	0.001
Green Diamond 10-yr-old	7.3	17.66	10.3	0.009
Green Diamond 25-yr-old	2.9	10.67	7.8	0.023
ODF W Oregon 18 yr old	0.1	04.79	4.7	0.001
ODF Kansas Creek 25-year-old	0.1	11.28	10.2	0.001
2003 Foliage				
Starker 10-yr-old	0	0.2	0.2	0.007
Starker 20-yr-old	0	2.1	2.1	0.180
Green Diamond 10-yr-old	1.0	13.3	12.3	0.004
Green Diamond 25-yr-old	0	0.7	7.0	0.025
ODF W Oregon 18-yr-old	0	0.7	0.7	0.002
ODF Kansas Creek 25-yr-old	0.2	1.8	1.6	0.010

Table 2. Comparison of *P. gaeumannii* incidence and infection index (incidence x severity) in sulfur sprayed vs. unsprayed foliage at six Oregon study sites. Significance levels are for a two-sample t-test comparison of means (sulfur vs. check) by foliage age class (Age classes 2002, 2003, 2004).

2005 Incidence	Starker 10	Starker 20	Green Diamond 10	Swede Hill 25	ODF Kansas Creek	ODF No Womans	P
AC 2004							**0.07**
Treatment	60.8	99	100	73.4	96.4	65.3	
Check	97.7	100	100	89.7	100	95.3	
AC 2003							**0.03**
Treatment	46.1	69.2	97.3	88	58.4	72.7	
Check	64.3	97	100	95.3	99.6	99	
AC 2002							**0.03**
Treatment	58.4	55.7	93.8	98.7	82.2	85.7	
Check	88.3	100	100	98.2	100	100	

2005 Infection Index	Starker 10	Starker 20	Green Diamond 10	Swede Hill 25	ODF Kansas Creek	ODF No Womans	P
AC 2004							**0.44**
Treatment	1.2	2.2	11.3	9.3	3.3	0.7	
Check	1.6	3.6	12.1	13	2.5	1.6	
AC 2003							**0.006**
Treatment	0.4	1.1	10.1	7.9	2.7	1.5	
Check	2.7	6.8	22.9	15.4	7.1	13	
AC 2002							**0.07**
Treatment	3.1	3.9	9.7	8.4	19.3	4.5	
Check	4.7	5.9		13	11.6	23.3	

year-old needles by *P. gaeumannii* at all six sites in both 2002 and 2003 (Table 1). Differences in infection levels of one-year-old foliage were significantly less for the sulfur treated foliage for all plot pairs except the Starker 20-year-old site in 2004 (P=0.18, Table 1). For the 2002 foliage at 12 mo following treatment, the magnitude of the differences in overall infection index varied from 4.7 for the ODF No Womans Land site to 12.1 for the Starker Forests 20-year-old plot pair. For 2003 foliage differences were somewhat smaller, 0.2-12.3 (Table 1). 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 for one-year-old 2002 needles sampled 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).

Large differences in incidence and infection index between sprayed and unsprayed foliage persisted for 2002 and 2003 foliage sampled in 2005. However, while mean infection levels were less for the sulfur-treated one-year-old 2004 foliage, which did not receive direct fungicide treatment, incidence was only marginally significant (P=0.07, paired t-test) and infection index was not significantly different (P=0.44, Table 2). Infection index was consistently smaller for the sulfur-treated plots, but differences were not great (Figure 1).

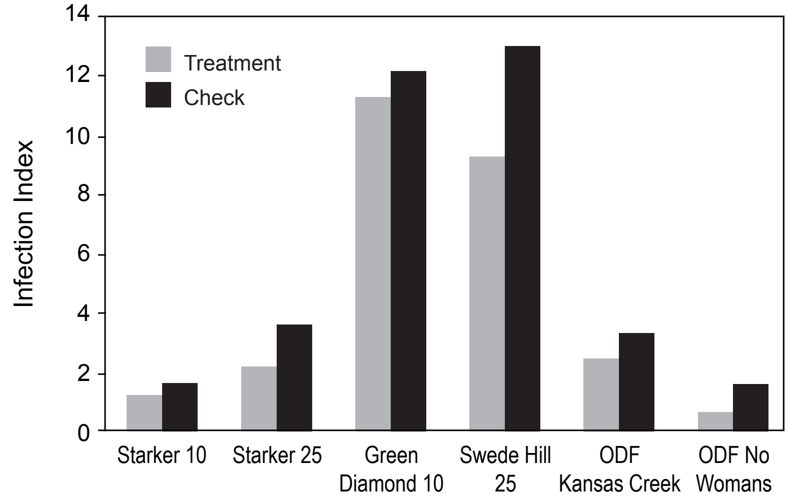

Figure 1. Comparison of P. gaeumannii infection index in one-year-old foliage (2004 foliage sampled in June 2005) for six sulfur treated and untreated plot pairs.

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 3000 BP (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 cytochrome b, 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. In the 2004 foliage, which did not receive direct fungicide treatment, the residual fungicidal effect appeared to be slight. After only one year, infection index was not statistically different between the sulfur treated and untreated plot pairs. In a similar study, after five annual applications of the fungicide chlorothalonil, which is generally more effective than elemental sulfur in reducing *P. gaeumannii* infection, infection levels were significanly less, and foliage retention significantly greater, in fungicide-treated vs. untreated units. However two years after fungicide applications had ceased, infection levels in one-year-old foliage were not significantly different (Stone et al. 2004).

Results of this study suggest that aerially applied elemental sulfur is effective in reducing foliage infection by *P. gaeumanii* in forest plantations, and may be a useful tool for SNC management, but the reduction is short lived. In addition to its effect in reducing foliage infection by *P. gaeumannii*, elemental sulfur may also increase foliage content of several elements, suggesting that it is also acting as a nutritional supplement (Stone et al. 2004).

Whether or not elemental sulfur will prove to be operationally useful 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. The results of this study and those of a previous study on fungicidal control of Swiss needle cast (Stone et al. 2004) suggest that fungicidal control of SNC can only be accomplished by continued or periodic fungicide applications 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 whether these effects persist following the cessation of applications.

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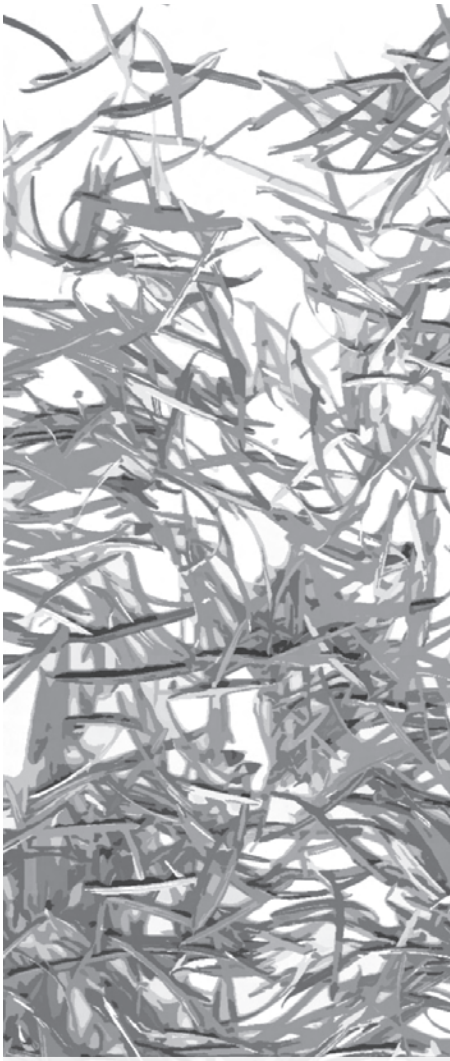

Using Hybrid Models to Predict Annual Stand-Level Growth Across a Range of Swiss Needle Cast Severity

Aaron Weiskittel, OSU; Doug Maguire, OSU; Robert A. Monserud, USDA-FS PNW Research Station

Introduction

The usefulness of empirical models of stand growth and yield are limited when they are applied to novel situations. For example, ORGANON has a good relationship with actual 5-year volume growth ($R^2 = 0.61$), but its bias is significantly related to foliage retention (Weiskittel and Maguire 2004). Hybrid models may offer an alternative to modifying empirical models to accommodate situations such as Swiss needle cast (SNC). In addition, these types of models allow for testing the influence of climate and other site factors on growth.

Manter et al. (2003) developed a carbon assimilation model to describe the impact of SNC and found a good relationship with actual volume growth ($R^2 = 0.79$). The model, however, required data not commonly collected (monthly soil water potential, pseudothecia density by foliage age class) for prediction of individual tree growth.

The objective of this study was to generalize the model of Manter et al. (2003) and test its performance. Key changes to the model were: (1) monthly to daily time step; (2) photosynthetic parameters were made a function of leaf nitrogen concentration using equations presented in Manter et al. (2005); (3) canopy absorbance of direct and diffuse radiation was calculated; (4) SNC severity was characterized by stand mean foliage retention rather than pseudothecial density; and (5) soil water content was treated as a function of soil depth and texture.

Table 1. Attributes of the 32 GIS and PCT plots used in this analysis.

Attribute	Mean	Standard deviation	Minimum	Maximum
		GIS (n = 13)		
DF stems per ha	558.6	318.0	197.6	1222.6
DF QMD (cm)	19.2	8.9	4.2	35.2
DF relative density	3.6	1.8	0.45	5.9
Foliage %N	1.37	0.17	1.11	1.61
Total age	20.0	4.4	15.0	29.0
Site index (m)	41.2	3.8	34.2	45.7
Foliage retention	2.3	0.7	1.4	3.1
		PCT (n = 19)		
DF stems per ha	1044.6	969.1	370.5	4322.5
DF QMD (cm)	13.6	2.7	9.1	17.9
DF relative density	4.1	3.5	1.3	16.4
Foliage %N	1.33	0.28	0.85	1.74
Total age	15.8	3.6	12.0	23.0
Site index (m)	37.7	4.9	30.3	45.0
Foliage retention	2.1	0.8	1.0	3.6

Methods

Thirty-two SNCC plots (13 GIS, 19 PCT) were used in this analysis (Table 1). These plots were chosen because they had been previously sampled for foliar nitrogen, a required model input. Both thinned and control PCT plots were simulated.

The Branch, Crown, And Canopy Simulator (BCACS; http://oregonstate.edu/~weiskita/bcacs.htm) was used to predict the required input for the Net Primary Production (NPP) model. Although site-specific climate does improve model performance, the daily climate in Tillamook for 2000 was used in this analysis for simplicity. The climate was generated using DAYMET (http://www.daymet.org/). As with climate, regional mean soils information was used for depth (1.5 m) and texture (50% silt, 20% clay) in place of site-specific values.

Results and Discussion

Predicted gross primary production (GPP) showed a good relationship with periodic annual increment (PAI; Figure 1). The overall R^2 was 0.76, but the relationship was much stronger (R^2 = 0.94) for the GIS plots rather than the PCT plots (R^2 = 0.32). The relationship was also sensitive to the method used for calculating stand respiration. For example, using the respiration algorithm outlined in Forest v5.1 (Schwalm and Ek 2004) the overall R^2 was reduced to 0.64, while calculating respiration similar to CABALA (Battaglia et al. 2004) produced an R^2 of 0.66. Although the relationship between NPP and PAI was similar for both approaches, the actual amount of respiration calculated varied greatly as Forest v5.1 and CABALA algorithms produced mean NPP to GPP ratios of 0.44 ± 0.09 and 0.30 ± 0.13. Although not mechanistically sound, it appears that calculating NPP as 0.47*GPP suggested by Waring et al. (Waring et al. 1998) may be the most reliable and reasonable approach for estimating respiration in these stands.

For comparison, a 3PG version parameterized for Douglas-fir was run on the output produced by BCACS. The model performed remarkably well; however, it produced a relationship between PAI and NPP not theoretically correct (Figure 2).

The second phase of this project will be to develop a carbon allocation algorithm and grow individual trees using the estimated stand-level NPP. In addition, model sensitivity to climatic and soil factors will be examined.

Both process-based models examined in this analysis (NPP and 3PG) appear quite capable of predicting annual stand-level growth across a range of Swiss needle cast intensity levels. Moreover, monthly pseudothecia density for each age class is not needed to accurately predict canopy-level carbon assimilation as mean foliage retention appears to perform equally well.

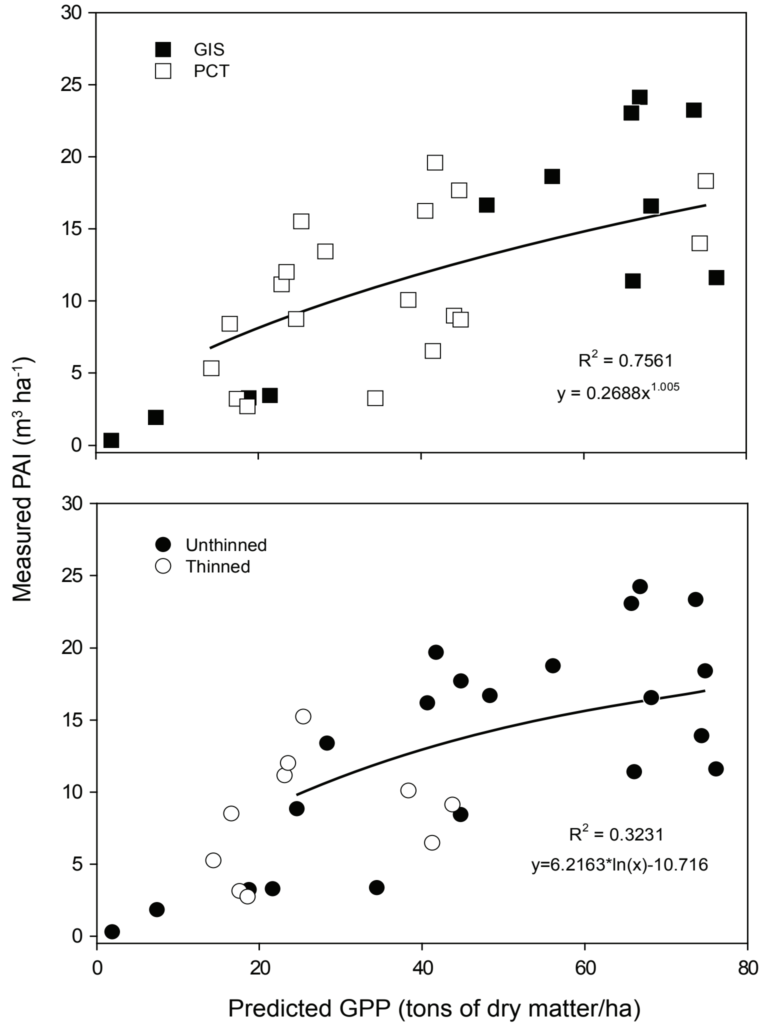

Figure 1. Plots of measured periodic annual increment (PAI) in 2000 (m^3 ha^{-1}) over predicted GPP (tons of dry matter per ha) for 13 GIS and 19 PCT SNCC plots. The top graph shows the pooled data, while the bottom graph shows the results for the thinned and unthinned PCT plots.

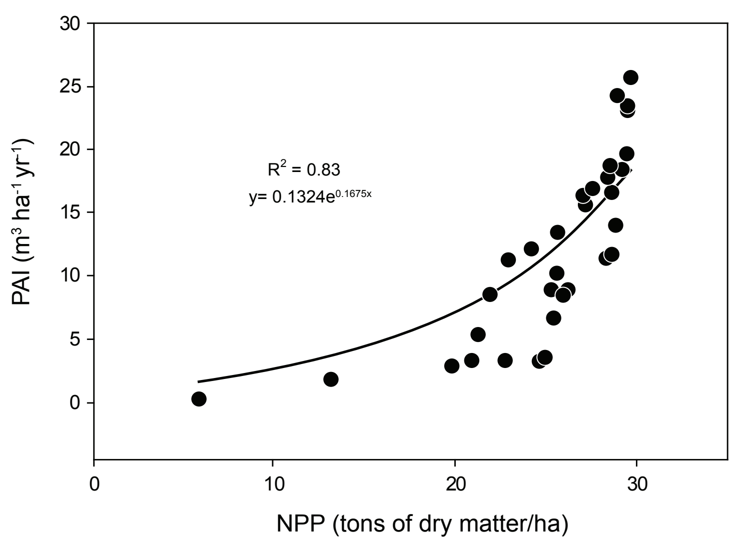

Figure 2. Plot of measured periodic annual increment (PAI) in 2000 (m^3 ha^{-1}) over predicted NPP (tons of dry matter per ha) for 13 GIS and 19 PCT SNCC plots using a 3PG model parameterized for Douglas-fir.

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Influence of Intensive Management and Sulfur Treatments on Douglas-fir Foliage

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Introduction

Specific leaf area (leaf area/leaf mass; $cm^2\ g^{-1}$; SLA) is an excellent indicator of needle physiology. In general, foliage with a low SLA has a greater net assimilation rate per unit of leaf area (Oren et al. 1986). Several environmental and stand factors influence SLA including sampling date, fertilizer treatment, species, and canopy position (Nippert and Marshall 2003). Weiskittel (2003) found SLA to be influenced by foliage age class, canopy position, tree size, site aspect, and Swiss needle cast (SNC) severity as measured by plot mean foliage retention. This study sought to understand the influence of intensive management practices and sulfur treatments and their interaction with SNC on Douglas-fir foliage.

Methods

The foliage samples used in this analysis came from the Menasha/COPE silvicultural plots (Mainwaring et al. 2004) and four of the paired plantations (Starker, Simpson, Tillamook, Western Oregon) treated by aerially applied elemental sulfur fungicide (Stone et al. 2004). The samples were taken from the fifth whorl from the tree tip in five dominant trees within each plot and 100 needles were randomly selected from the one- and two-year-old foliage age classes on each branch. Fresh needle samples were measured using an image analysis system and dried at 70ºC for 48 hours and weighed to the nearest 0.001 g.

Treatment combinations examined in the Menasha installations were: (1) PCT, prune, fertilized; (2) PCT, prune, no fertilized; (3) PCT, fertilized; (4) PCT, not fertilized; (5) fertilized; and (6) control. Treatment combinations examined in the sulfur treatment plots were: (1) young (15-20 yrs. old), unthinned control; (2) young unthinned, sulfur treated; (3) mature (20-25 yrs. old), thinned control; and (4) mature thinned, sulfur treated. Treatment effects were assessed using ANOVA, after accounting for installation and foliage age effects.

Results and Discussion

Mean SLA was 70.7 ± 11.1 and 67.7 ± 12.58 for the Menasha and sulfur plots, respectively. These values are similar to the mean value (70.2 ± 20.2) reported in Weiskittel (2003). No treatment combination in either the Menasha or sulfur studies had a significant effect on SLA for either foliage age class (Figure 1). This conclusion is similar to the observations of Manter et al. (2005) who found that Douglas-fir seedlings had similar SLA values despite being treated with varying levels of nitrogen fertilization.

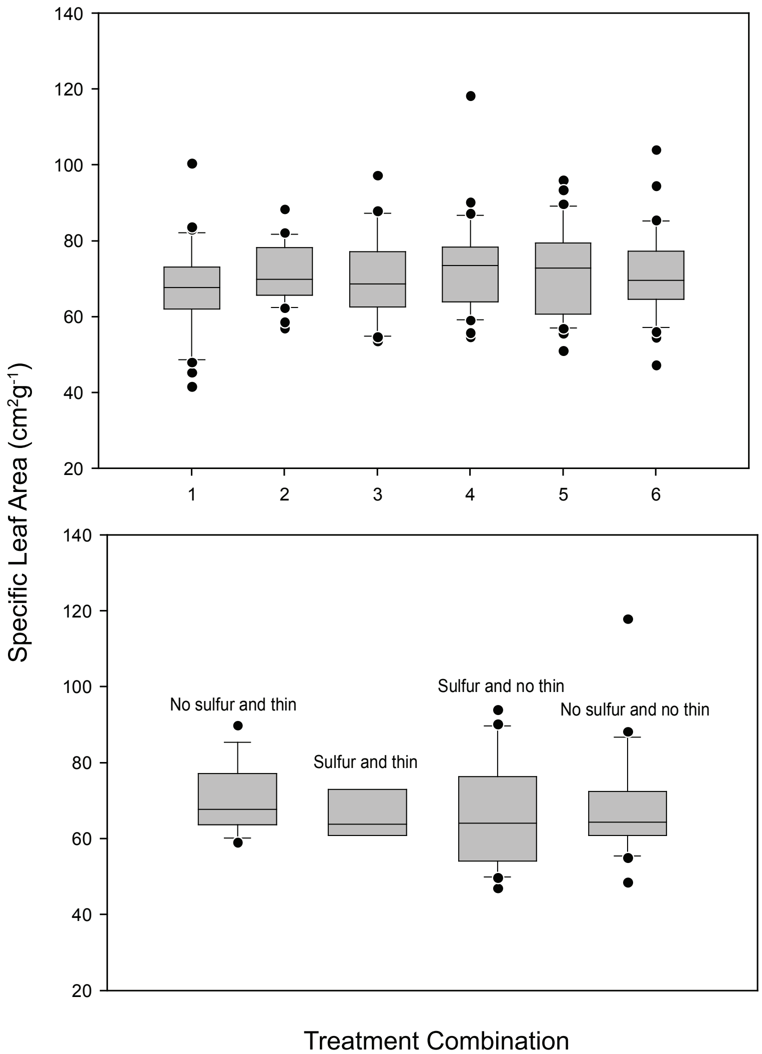

Figure 1. Plots of specific leaf area (cm^2 g^{-1}) over treatment combination for the Menasha (top) and sulfur (bottom) installations.

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Interactive Effects of Swiss Needle Cast and Commercial Thinning on Douglas-fir Growth and Development in North Coastal Oregon: Two Year Response from 30 Permanent Monitoring Plots, 2005

Doug Mainwaring, Doug Maguire, Alan Kanaskie, Jeff Brandt

Abstract

Thirty pairs of permanent monitoring plots were established in the winters of 2001 (period 1: 2002-2003) and 2002 (period 2: 2003-2004) to assess the growth of Swiss needle cast (SNC)-infected Douglas-fir stands (aged 20-60 yrs) scheduled for commercial thinning.

Model-implied foliage retentions on thinned plots increased relative to controls during both periods. However, during growth period 1, foliage retention decreased in stands with initial foliage retentions below ~2.65 years, with a maximum average loss of 0.2 years in the most heavily infected stands (folret= 1.3 yrs). In contrast, during growth period 2, foliage retentions increased at all levels of initial foliage retention (average: 0.27 yrs), with the increase being slightly greater at higher levels of SNC infection.

Volume growth during both growth periods was found to decline with increasing intensity of SNC, as measured by initial foliage retention and crown sparseness. Volume growth losses in the most heavily infected stands, assuming no change in foliage retention, were approximately 32% compared to uninfected stands. However, actual growth losses during the two periods differed significantly, as a result of increases in foliage retention during the second growth period. When accounting for average changes in foliage retention during the two periods, period 1 losses in the most heavily infected stands were 37%; for equally infected stands in period 2, losses were 31%.

Absolute levels of volume growth were significantly greater (~25%) during the 2003-2004 period at all levels of SNC infection. Although individual tree analysis confirmed that thinning had a significant effect on growth, because post-thinning growth depends on the net effect of basal area removal and lower stand basal area, trees may respond either positively or negatively to thinning depending on the level of these two variables. Importantly, this effect is independent of the level of Swiss needle cast. The individual tree analysis confirmed that thinning should be done from below.

Introduction

Many Douglas-fir (Pseudotsuga 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 since 1990 (Hansen et al. 2000). The 2004 aerial survey indicated that approximately 177,000 acres out of the 3 million acres surveyed in Oregon showed detectable discoloration, a decrease from the previous high of 388,000 acres in 2002 (Kanaskie et al. 2004b).

Of greatest concern are the approximately 188,000 acres 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. 2004a), 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 363,000-ac 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 356,000 ac from 1933-1951 (Fick and Martin 1993). In the approximately 235,000-ac 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 in 2003, looked at the thinning response of stands treated 4 to 10 years prior. These stands 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. 2005). 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 six different northwestern Oregon ODF districts (Tillamook, Forest Grove, Astoria, West Oregon, Santiam, Coos), five of which include land in the Coast Range. The Santiam district is located entirely within the Cascades, and was included due to evidence of a light infection level in this province (Freeman 2002). Plots were distributed from 43.58°to 46.16° N latitude and from 124.06°-122.5° W longitude, and from 200 to 2500 ft above sea level (Figure 1). Over the last 40 years in this region, the mean January minimum was 36° F and the mean July maximum was 77° F. Total annual precipitation averaged 60-120 inches, with approximately 70% of the total falling from October to March.

Thirty pairs of fixed area plots were established during the winters of 2001 (2002-2003 period) and 2002 (2003-2004 period) (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 the growing season. Plot locations were chosen from among candidate timber sales, or areas where lack of planned activities made them available for a plot-only thinning.

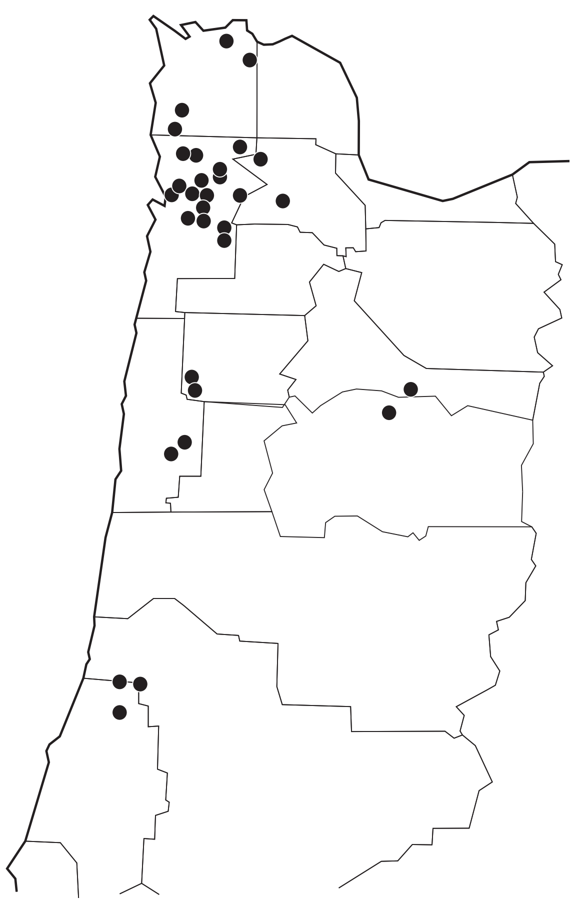

Figure 1. Paired plot locations in thinning study

In a representative part of each stand, two square, 0.5 ac plots were established, each with a 70 foot buffer, for a total of a 2 acre treatment area (Figure 2). Where possible, the treatment plot was contiguous to the control plot. Measurements were confined to the inner 0.5-ac 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 was 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.

Table 1: plot characteristics

Plot	Trt	ODF dist	Vol PAI (ft³/acre)	Site index (ft/50y)	RD (at thin) ($ft^2/ac/in^{0.5}$) (Curtis 1982)	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)	Period
Barksh100	cont	Till	376.2	131.5	57.7	11.1	1.7	7.2	189.9	0	28.2	2
Barksh100	thin	Till	303.1	138	33.9	11.5	2.3	4.6	125.5	0	29.2	2
Barksh140	cont	Till	376.2	131.5	57.7	11.1	1.7	7.2	189.9	0	28.2	2
Barksh140	thin	Till	229.3	136.2	36.8	12.1	1.9	5.9	127.5	0	30.9	2
Benson N	cont	Coos	342.1	135.7	51.4	11.8	2.8	4.9	180.6	0	30	2
Benson N	thin	Coos	266.8	134.8	37	9.4	1.9	5.3	111.2	3.1	23.8	2
Benson S	cont	Coos	434.9	147.2	63.9	7.8	2.3	5.3	183	0.5	19.8	2
Benson S	thin	Coos	273.5	159.7	32.3	8.4	2.2	6.9	105.4	1.3	21.4	2
Brownsmd	cont	Ast	240.4	151.3	64.7	12.7	2	5.8	166.7	60.6	32.2	1
Brownsmd	thin	Ast	195.1	151.3	32.7	12.5	2.1	5	120.8	0.4	31.7	1
Clammer	cont	Till	207.4	146.2	65.1	11.4	2	4.9	159.5	65.3	29	1
Clammer	thin	Till	98.8	139.8	27.8	13.4	1.9	5.5	84.8	14.3	34	1
Cook wright	cont	Till	196.6	134.2	63.6	11.5	1.8	8.3	152.2	50	29.2	1
Cook wright	thin	Till	71.4	128.3	24.8	11.2	2.2	7	59.8	24.5	28.3	1
County Line	cont	Till	216.7	135.1	50.6	11.5	1.7	5.6	158	23.2	29.3	2
County Line	thin	Till	130.9	127.9	29.7	12.4	1.4	8	85.9	14.2	31.6	2
Deer Creek	cont	WO	374.4	144.8	52.1	9.1	2.9	5.7	168.5	1.3	23.1	2
Deer Creek	thin	WO	212	148.5	26.8	9	2.6	5.9	91.4	0	22.8	2
Toll Road	cont	Till	235.4	135.9	47	11.1	1.9	4.4	163.9	6.9	28.3	1
Toll Road	thin	Till	108.5	138.7	26.3	11.6	1.5	4.5	83.5	11.4	29.4	1
Fall Hatch	cont	WO	256.9	132	68.5	23.7	2	5.5	290.5	1.6	60.1	1
Fall Hatch	thin	WO	107.7	132.9	22.4	23.8	2	7	110.6	0	60.4	1
Gales Creek	cont	FG	261	142.3	53.2	18.7	3.9	4.4	205.5	12.5	47.5	1
Gales Creek	thin	FG	155.1	144.1	29.2	18.9	3.7	5.4	129.2	0	48	1
Gold Peak	cont	Till	254.3	139.9	46.1	12.9	2	4.7	179.1	0	32.8	1
Gold Peak	thin	Till	170.2	134.2	43.4	12.2	2	5	163	0	31	1
Gwave	cont	Sant	297.2	120	58.3	16.1	3.7	4.7	200.1	3.8	40.8	2
Gwave	thin	Sant	221	119.7	33.2	15.9	3.6	4.3	120.4	3.5	40.5	2
Hagg Lake	cont	FG	339.7	134	64.9	17.3	4.3	5.2	241.2	0	44	1
Hagg Lake	thin	FG	201.8	129.7	31.6	16.6	4.3	3.7	128.4	0	42.2	1
Hatcom	cont	WO	293	128.4	43.2	8.1	1.5	4.8	135.9	9.3	20.6	2
Hatcom	thin	WO	255.8	131.3	34.5	9.2	1.9	5.2	122.2	0.5	23.3	2
Kilchis	cont	Till	198.8	123.8	63.7	12.9	1.4	7.2	200.4	0	32.7	1
Kilchis	thin	Till	112.1	131	39.1	11.8	1.7	6.5	127.0	0	30	1
Lower Wolf	cont	WO	330.9	155.7	72.6	21.4	3.3	4.8	303.0	18.1	54.3	1
Lower Wolf	thin	WO	157.1	152.1	29.8	21.9	2.7	5.5	144.7	0	55.6	1
Miami Stu	cont	Till	195.2	124.1	44.9	13.3	1.3	4.3	155.8	17.3	33.8	1
Miami Stu	thin	Till	77.4	123.3	25.6	12.8	1.5	5.1	76.4	23.2	32.6	1
OSP	cont	Till	228.8	100.1	66.4	14.3	2.3	5.7	244.4	0	36.3	2
OSP	thin	Till	167.6	116.6	47.8	15.0	2.1	7.8	167.1	21.1	38	2
Phipps Cr	cont	Till	315.4	134.2	58.2	18.8	2.6	6.3	210.6	1	47.9	2
Phipps Cr	thin	Till	277.7	133.9	41.8	18.4	3	7.1	161.3	0	46.9	2
Sam Downs	cont	Till	152.5	125.4	57.3	12.3	1.5	5.4	167.2	16.4	31.3	1
Sam Downs	thin	Till	97.2	132.8	38.3	12.7	1.3	6.5	107.5	19.6	32.1	1
Schmitz	cont	Till	387.7	132.2	74.5	13.2	1.8	8.9	242.8	0	33.4	2
Schmitz	thin	Till	282.4	140.6	38.7	12.9	1.5	8	139.8	0	32.9	2
Soapstone	cont	Ast	198.3	142	64	13.7	1.9	7.5	192.7	37.3	34.8	1
Soapstone	thin	Ast	164.9	146.8	42.8	13.0	1.8	8.5	153.9	0.2	33	1
Swmisc	cont	Till	162.5	126.6	38.3	13.6	1.8	4.9	106.4	39.2	34.7	2

continue Table 1

Plot	Trt	ODF dist	Vol PAI (ft^3/acre)	Site index (ft/50y)	RD (at thin) ($ft^2/ac/in^{0.5}$) (Curtis 1982)	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)	Period
Swmisc	thin	Till	192.5	115.3	35	13.4	1.7	4.7	136	0	34.1	2
Tom rock	cont	Sant	189	119.7	71.4	23.4	3.2	9.7	235.6	20.2	59.4	1
Tom rock	thin	Sant	143.1	131.8	37.9	23.5	3.2	10.1	137.6	12.5	59.8	1
W Standard	cont	Till	384.7	139.7	73.4	13.7	3.7	6.9	241.2	7.6	34.8	2
W Standard	thin	Till	320.7	145.8	37.9	13.8	2.9	7.1	141.1	0	35	2
West fork	cont	Coos	416.9	127.3	61.7	11.6	2.9	4.3	205.6	4.3	29.4	2
West fork	thin	Coos	90.4	143	16.4	11.5	2.3	6.1	53.7	6.3	29.3	2
Westport	cont	Ast	308.2	143.5	54.2	10.9	3.6	5.4	176.0	22.7	27.8	1
Westport	thin	Ast	260.8	136.4	33.6	10.4	3.5	4.6	130.0	0.1	26.4	1
Wwheel	cont	FG	312.6	128.3	77.5	23.8	4.6	6.6	271.4	35	60.4	2
Wwheel	thin	FG	159.9	130.7	35.8	23.0	4.5	9.6	139.1	13.9	58.4	2
Mean			233.1	134.8	46.5	14.1	2.4	6.0	158.4	10.4	35.8	
Max			434.9	159.7	77.5	23.8	4.6	10.1	303	65.3	60.4	
Min			71.4	100.1	16.4	7.8	1.3	3.7	53.7	0	19.8	

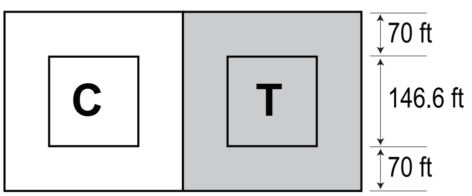

Figure 2. Dimensions of paired plot thinning study

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

After adjusting for changes in control plot foliage retention, the change in foliage retention on thinned plots did not show an obvious pattern in relation to initial foliage retention (Figure 3). Any measured changes at the block level were apparently the result of local infection levels rather than treatment. That said, whereas changes during the 2002-2003 period were both positive and negative, changes during the 2003-2004 period were generally positive on both control and treatment plots (Figures 4-5).

When analyzed as a randomized block experiment with initial foliage retention as a covariate, block effects were significant in explaining the change in foliage retention (R^2=93%), but treatment effects were not. 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 49% of the variation in the change in the logarithm of foliage retention was explained by the following model (MSE = 0.0589):

[1] $(dFOLRET) = a_0 + a_1(BADF) + a_2(FOLRET) + a_3(CLSA) + a_4(CUTBA) + a_5(GRPER) + a_6(GPFR)$

where
- dFOLRET = Change in foliage retention (years)
- BADF = Douglas-fir basal area per acre (ft^2)
- FOLRET = Current average foliage retention for the plot (yrs)
- CLSA = Crown sparseness (cm/cm^2)
- CUTBA = Removed basal area per acre (ft^2)
- GRPER = 1 if growth period is 2003-2004, 0 if otherwise
- GPFR = Interaction term: GRPER*FOLRET

Parameter estimates (table 2) indicated that the change in foliage retention over two years increased with greater initial foliage retention (during the first growth period) and crown sparseness, and decreased with increasing Douglas-fir basal area and thinning intensity. The growth period indicator variable and its interaction with foliage retention indicates that the change in foliage retention was more positive during 2003-2004 than 2002-2003, but

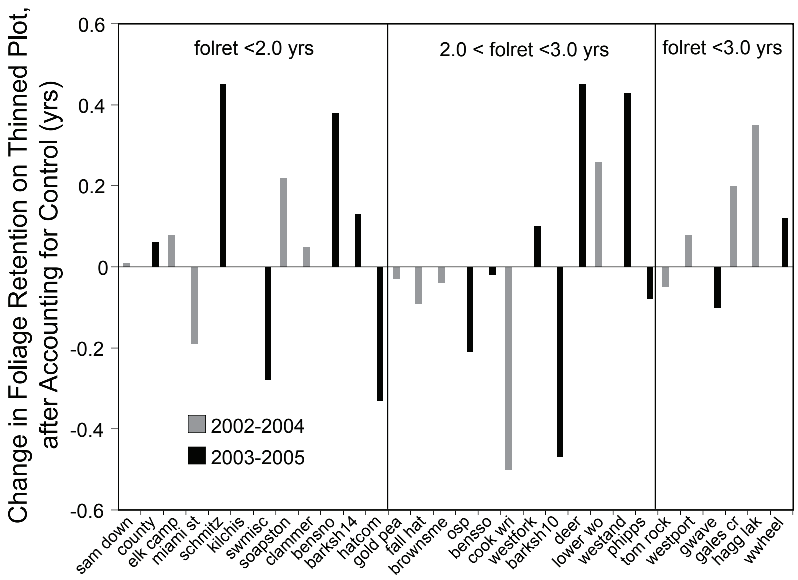

Figure 3. Change in foliage retention for thinned plots vs. controls: plot summary.

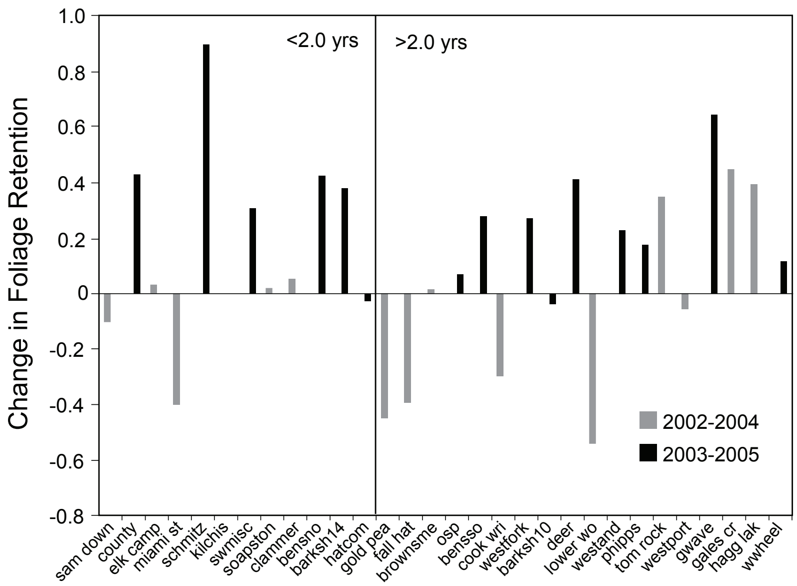

Figure 4. Change in treatment plot foliage retention

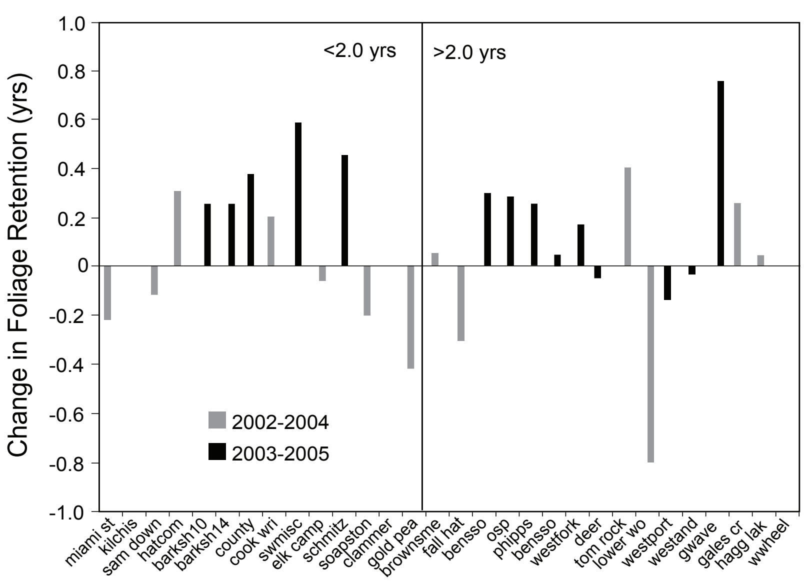

Figure 5. Change in control plot foliage retention

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

Variable	Parameter Estimate	Standard Error
a_0	-0.27681	0.20350
a_1	-0.00810	0.00098
a_2	0.18808	0.05404
a_3	0.06225	0.02369
a_4	-0.00222	0.00091
a_5	0.79727	0.18395
a_6	-0.19720	0.07192

that the difference between periods decreases as foliage retention increases (Figure 6). Healthy stands behave similarly in the two growth periods. However, during the first growth period, heavily infected stands tended to lose foliage retention and during the second growth period, heavily infected stands responded similarly to healthy stands. Because removal of basal area (represented by CUTBA variable) implies a lower initial basal area when comparing a thinned stand to the same stand without thinning, the net effect is an increase in foliage retention with thinning .

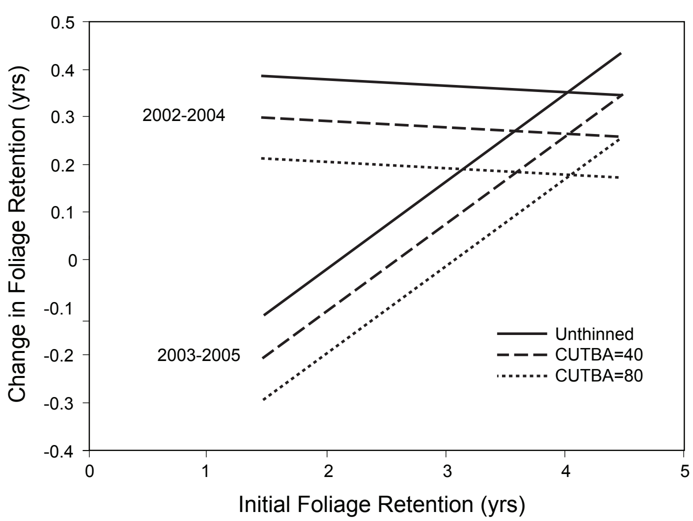

Figure 6. Change in foliage retention for unthinned and thinned plots implied by equation [1], assuming mean values for CL:SA (6.0 cm/cm²). Unthinned plot is based on 200 ft² of basal area, light thinning (CUTBA=40 ft²) is based on 160 ft² of basal area, and heavy thinning (CUTBA=80 ft²) is based on 120 ft².

Periodic volume increment

Treated as a randomized block experiment, both plot and treatment effects were significant in explaining volume increment. However, when initial Douglas-fir basal area was included as a covariate, treatment effect was no longer significant. 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, age, and growth period.

Approximately 92% of the variation in the logarithm of periodic annual volume increment was explained by the following model (MSE = 0.018):

2] $\ln(VPAI) = b_0 + b_1\ln(BADF) + b_2\ln(SI) + b_3\ln(FOLRET) + b_4\ln(CLSA) + b_5(AGE) + b_6(GRPER) + b_7(dFOLRET)$

where VPAI = Periodic volume increment per acre (ft³/ac/yr)
SI = 50 yr site index (ft) (Bruce 1981)
AGE = Breast height age, plot average (yrs)

And BADF, FOLRET, CLSA, GRPER, and dFOLRET are as defined above

Parameter estimates (Table 3) indicated that periodic annual volume increment increased with increasing Douglas-fir basal area, site index, and foliage retention, and decreased with increasing crown sparseness, and age. The significance of the growth period indicator variable and dFOLRET indicates that while stands were more productive during the 2003-2004 period generally, part of the difference between the growth periods was due to foliage retention changes (Figure 7). The model implies that heavily infected stands suffering foliar losses similar to the 2002-2003 growth period (as portrayed in Figure 2) would have a 6% greater growth loss than if the stand had experienced a foliar retention change similar to the 2003-2004. When compared to a healthy stand (represented by mean SNC index values from Gales Creek, Hagg Lake, Westport, and Waterwheel, West Standard, and Green Wave: Foliage retention: 3.9 years; CL:SA 5.7 cm/cm²), growth losses

Table 3. Parameter estimates for model describing periodic annual volume increment (equation[2]).

Variable	Parameter Estimate	Standard Error
b_0	-6.1381	1.2395
b_1	0.9626	0.0546
b_2	1.4702	0.2427
b_3	0.2170	0.0671
b_4	-0.2577	0.0854
b_5	-0.0115	0.0023
b_6	0.1713	0.0689
b_7	0.2936	0.0460

in heavily infected stands (folret=1.3 yrs, CL:SA=10 cm/cm^2) are implied to be 32%, assuming no change in foliage retention (Figure 8).

Individual tree growth

In order to determine how individual trees are responding to treatment, an individual tree model was constructed using the subset of trees which had been measured for height and height to lowest live branch on each plot. Approximately 79% of the variation in the logarithm of periodic annual volume increment was explained by the following model (MSE = 0.249):

$$[3]\quad \ln(VPAI) = c_0 + c_1\ln(DBH) + c_2\ln(CR) + c_3(BAL) + c_4\ln(SI) + c_5\ln(BAtotal) + c_6(CUTBA) + c_7\ln(FOLRET) + c_8(DBHFR) + c_9(GRPER) + c_{10}(GPCUTBA)$$

where	DBH	=	Diameter at breast height (in)
	CR	=	Crown ratio
	BAL	=	Basal area in larger trees (ft^2/ac)
	BAtotal	=	Basal area, all species (ft^2/ac)
	DBHFR	=	Interaction term: ln(DBH)*ln(FOLRET)
	GPCUTBA	=	Interaction term: GRPER*CUTBA

And VPAI, SI, CUTBA, FOLRET, and GRPER are as defined above

Parameter estimates 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 in larger trees, and removed basal area. The growth period indicator variable and its interaction with removed basal area indicates that all else being equal, trees were more productive during the 2003-2004 growth period than the 2002-2003 growth period, and that this difference is at least partially attributable to better response from similar levels of thinning intensity.

The interactive effect of foliage retention and tree size implied by the marginally significant DBHFR variable (p=0.064) is shown in Figure 9. As diameters decrease, trees in infected stands 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.

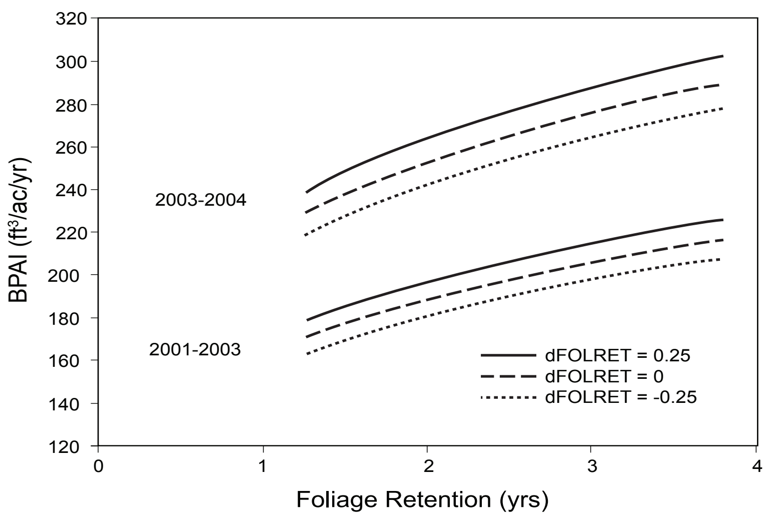

Figure 7: Periodic annual volume increment per period implied by model [2], assuming mean values for Douglas-fir basal area (158.4 ft^2/acre), site index (134.8 ft, 50 yrs.), CL:SA (6.0 cm/cm^2), and age (35.8 yrs).

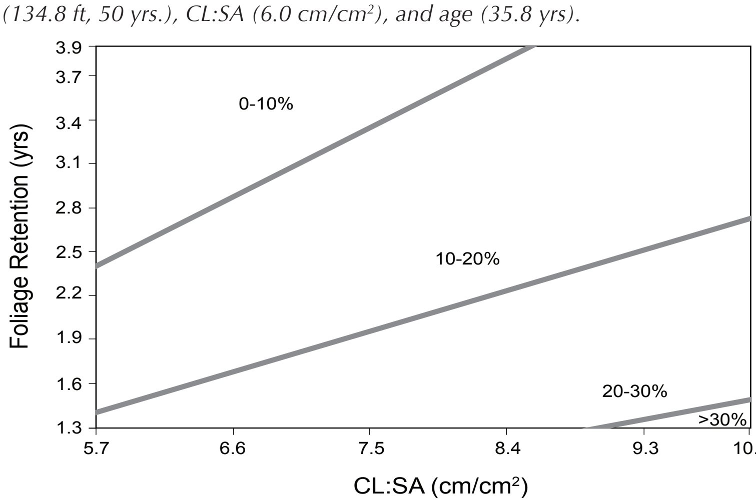

Figure 8. Volume growth loss by foliage retention and CL:SA, implied by model [2], assuming mean values for Douglas-fir basal area (158.4 ft^2/acre), site index (134.8 ft, 50 yrs.), and age (35.8 yrs), and no change in foliage retention.

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

Variable	Parameter Estimate	Standard Error
c_0	-13.58911	0.79291
c_1	2.70318	0.08642
c_2	0.49616	0.04725
c_3	-0.00131	0.00030
c_4	2.01783	0.14229
c_5	-0.42091	0.07404
c_6	-0.00312	0.00047
c_7	0.55977	0.24167
c_8	-0.16768	0.09054
c_9	0.43254	0.03018
c_{10}	0.00106	0.00041

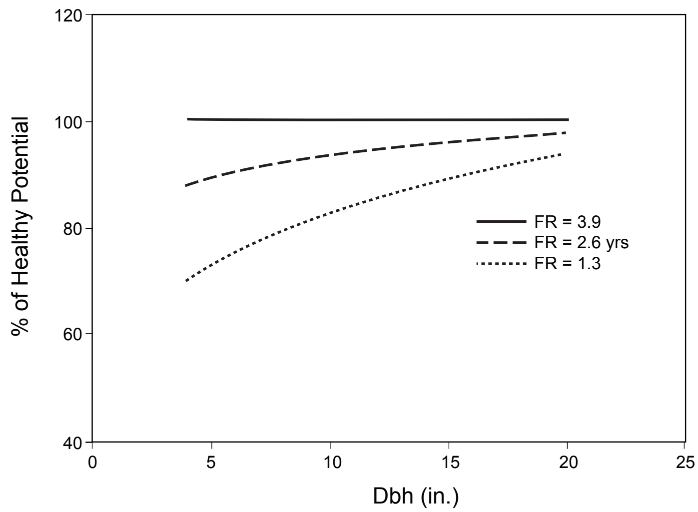

Figure 9. Percent of healthy growth by dbh exhibited by SNC-infected trees in thinned and unthinned stands implied by model [3].

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 equation [1] implies that thinning has a positive effect on foliage retention, actual changes in foliage retentions were very different in the two growth periods. During 2002-2003, the change is negative at low foliage retentions of thinned and unthinned stands. Nevertheless, this change is small, amounting to a maximum average negative effect of about 0.2 years on thinned plots in the most heavily infected stands. In contrast, during the 2003-2004 growing seasons, the average treatment response was an increase of almost 0.3 years, and was slightly greater for low foliage retention stands.

Results from the retrospective phase of this study indicated that at a foliage retention of 1.65 years and a crown sparseness of 10 cm/cm^2, a stand thinned 4-10 years previous would be producing an average of 22% less volume than an uninfected stand with a foliage retention of 3.65 years and a crown sparseness of 7 cm/cm^2. Using the same values of foliage retention and CL:SA, the model-implied volume loss for the two growth periods between 2002 and 2004 is 23%, assuming no change in foliage retention (equation [2]). Applying foliage retention changes during the two growth periods (as implied in Figure 2 for a moderate thinning: 40 ft^2), comparable losses during the 2002-2003 growing seasons are 29%, versus only 23% for the 2003-2004 growth period. A direct comparison between the results from the permanent plots and the retrospective study isn't possible due to the unknown change in foliage retention following harvest of the retrospective stands. However, these results certainly indicate that the 2003-2004 period reflects a significant improvement relative to the 2002-2003 period—primarily the result of improved foliage retention. The reasons for this increase are unknown, but are consistent with the results from the aerial survey (Kanaskie et al. 2004b).

Other evidence suggests that improved foliage retention is only part of the explanation for a trend of growth improvement in the epidemic area. Volume growth losses on the Swiss needle cast Cooperative's permanent monitoring plots diminished in the 2002-2003 period relative to two previous 2-year growth periods, given equivalent levels of foliage retention. In the 2000-2001 growing seasons, model-implied mean volume growth losses for a stand with a foliage retention of 2.0 yrs were 29%. In the 2002-2003 growth period, stands with a similar level of foliage retention had a model-implied volume growth loss of 21%. Improved growth per year of foliage retention was explored with the permanent plot data by adding a foliage retention/growth period interaction term to equation [2]. It was not significant ($p\sim0.13$), but even after accounting for the change in foliage retention, its low p-value is at least suggestive of greater foliar efficiency.

The growth improvements measured in recent years mirrors the less-precisely measured decreases in SNC-impacted acreage as determined by aerial survey. From a high of 387,000 acres of high and moderately diseased stands in 2002, acreage totals for subsequent years were 268,000 and 177,000 (Kanaskie et al. 2004b). Part of these smaller totals are the result of liquidation of the most heavily impacted stands. Such stands, generally replanted with western hemlock, directly reduce impacted acreage totals. A secondary effect from such liquidations is a likely decrease in the Phaeocryptopus spore load, albeit unmeasured.

A general improvement in growing conditions is indicated by the fact that model-implied growth for stands at all levels of infection is approximately 25% greater in the 2003-2004 period than the 2002-2003 period. This increase reflects differences between the 2002 and 2004 growing seasons, and is likely the result of above average growing season precipitation in the Coast Range during 2004. According to archived data from weather stations throughout the study area (Nehalem, Otis Junction, Seaside, Tillamook, Willamina), average May-August precipitation during 2004 was 2.0 and 2.9 times greater than the comparable periods in 2002 and 2003 respectively (http://www.ocs.oregonstate.edu/index.html). Although this increase in available water had a significant effect on volume response in 2004, there may be a downside. Spring leaf wetness during the period of Phaeocryptopus spore release (May-July) is positively correlated with Phaeocryptopus germination (Manter et al 2003). If this wet weather increased spore germination in 2004, its effects will not be apparent until the next 2-yr remeasurement. It may be complicated by the fact that May and June of 2005 have thus far been wetter than average.

Construction of a comprehensive model to account for both growth periods changed the reported results from the 15 plots measured during the first growth period. For the plots monitored during the 2002-2003 seasons, thinning was reported to have had a significant negative effect on volume growth. While it continues to be true that infected thinned stands produce less volume than healthy thinned stands on a percentage basis than is true for infected unthinned stands, after additional analysis of the first period data, the effect of thinning on volume growth of individual trees was inconclusive after accounting for initial and removed basal area.

The CUTBA variable in equation [3] indicates that BA removal does affect the growth of individual trees. Comparing similar trees in thinned and unthinned stands of similar initial basal area, the equation implies that the effect of BA removal may be positive or negative, depending on the net effect of initial stand basal area and level of the removal. An important point is that this effect occurs at all levels of foliage retention: it is independent of SNC infection level.

Two-year growth of recently-thinned stands without SNC doesn't reflect the full growth potential gained from spacing the residuals. 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). Nevertheless, results from the retrospective study, based on 4 to 10 years of growth following thinning, indicate similar levels of growth loss when comparing stands with similar levels of infection.

The significant negative interaction between foliage retention and diameter implies that small trees suffer more growth loss with SNC infection than large trees. This suggests that thinning in SNC-infected stands should be done from below. 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, this is not the case (Figure 9). This is consistent with previous work in genetics: heritability studies have shown that the best single trait to select for would be basal area increment (Johnson 2002). 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. As a result, tree differentiation since the onset of the SNC epidemic in 1990 (Maguire et al. 2002) makes it possible to identify tolerant trees. Applied to structural development, this means that retention of the largest Douglas-fir during a conventional thinning or type I harvest can be done without fear of an ongoing negative response.

Although the results from this period are suggestive of an improvement in the growth of SNC-infected Douglas-fir, it has been suggested that this is a common occurrence in disease cycles (Willis Littke, Pers. Comm.). Pressure from the pest decreases as susceptible hosts are reduced in number (via harvest), leading to improvement in disease conditions and the health of remaining hosts. However, the strong economic incentive to replant Douglas-fir in areas more appropriate for non-susceptible species could reinvigorate the pest. Because species conversion has already been undertaken in stands where SNC was especially bad, and where Douglas-fir would be considered most offsite, the likelihood of this being a major problem in the immediate future is reduced.

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Foliage Retention on Branches Sampled in 2005 Compared to Ground-Based Estimates from 2004

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Abstract

Permanent plots in the Growth Impact Study and Pre-Commerical Thinning study have been rated annually for Swiss needle cast (SNC) severity, starting in 1998. In spring 2005, ground-based ratings were abandoned due to the difficulty of accurately estimating foliage retention as crowns receded. Instead, one sample branch was collected in spring 2005 from the fifth whorl of five of the original SNC rating trees on each plot. Mean foliage retention based on sample branches was generally consistent with foliage retention estimated from the ground in spring 2004.

Introduction

The Growth Impact Study (GIS) was initiated in 1997 to monitor Swiss needle cast (SNC) symptoms and tree growth in 10-30-yr-old Douglas-fir plantations, and the Pre-Commercial Thinning Study (PCT) was initiated in 1998 to test the effect of thinning and initial SNC severity on symptom development and growth response. In both studies, the primary index of SNC severity has been foliage retention. This index has been estimated on ten standing trees per plot by dividing the tree crown into thirds vertically and visually estimating average retention on representative branches, ignoring the main axis of the primary branch. Ratings from each third are averaged for a tree-level rating, and the ten sample trees from each plot are averaged for a plot-level rating.

As subject stands have developed over the past seven years, crown recession has kept pace with height growth to the extent that our confidence in the ground-based foliage retention has continued to erode. The decision was made in 2005 to switch to plot ratings based on various attributes measured on 5-yr-old whorl branches removed from the tree. The objective of this report is to test for differences in relative SNC severity (foliage retention) between the ground-based procedure and the lab analysis of sample branches. No test was run for possible bias between the two procedures because they were sampled in two different years and SNC severity has been show to fluctuate considerably from year to year.

Methods

In early spring 2004, all 72 GIS and 51 PCT plots were rated for SNC severity following the protocol established early in the SNC research program (Maguire et al. 1998, 2002). Briefly, the crown was divided into an upper, middle, and lower third, and average foliage retention on branches of second and higher order was estimated in each third to the nearest 0.1 yr. Retention was estimated on the same ten trees that have been rated annually since 1998 and that were originally selected from the dominant/codominant classes. The mean rating was then computed for each tree and plot.

In late winter/early spring of 2005 five of the ten SNC rating trees in each plot were randomly selected and then climbed to collect a 5-yr-old whorl branch. The branch was cut flush with the bole, then wrapped in a plastic bag and placed in a cooler for transport to the lab. In the lab, each branch was rated for average foliage retention, and plot-level retention was computed from the five sample branches collected from each plot.

Foliage retention estimated from the ground in 2004 was plotted on foliage retention estimated from sample branches in 2005. Correlations and rank correlations were run for the two datasets (GIS and PCT) separately. The implied distribution of the population acreage by SNC severity was also computed for the GIS plot based on both the ground- and branch-based retention ratings.

Results and Discussion

The 2004 ground-based estimates of foliage retention were closely correlated with the 2005 branch-based estimates (Figure 1). Correlation coefficients between ground-based and branch-based foliage retention were 0.769 for the GIS plots and 0.924 for the PCT plots. Corresponding rank correlations were 0.761 and 0.922, respectively. Visual access to the crown may have contributed to the difference in correlation strength between GIS and PCT plots. Average height to crown base for the GIS plots was 6.0 m and ranged from 0 to 20.7 m. In contrast, average height to crown base for the PCT plots was 3.8 m and ranged from 0 to 11.9 m. Visibility of retention was therefore better for the lower crowns of PCT plots. However, the wider range in retention on PCT plots may also have contributed to their higher correlation (Figure 1). The 1:1 line assuming perfect correspondence between the two estimates of foliage retention is slightly different from the regression line through the GIS data, perhaps due in part to a regional improvement in foliage retention from 2004 to 2005 (Figure 2). However, the PCT data are less clear and suggest that foliage retention on control plots was very consistent between years, and that foliage retention may have declined on thinned plots (Figure 3).

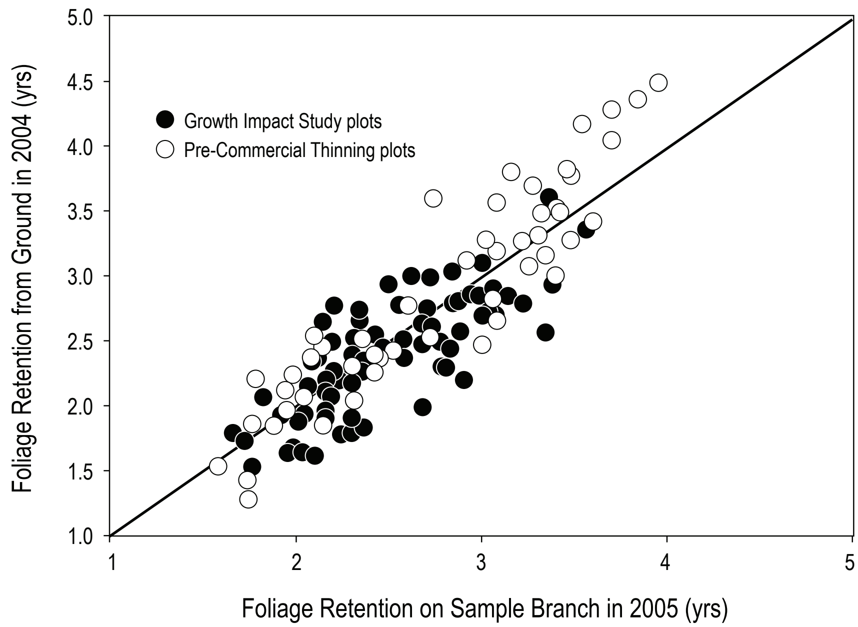

Figure 1. Relationship between foliage retention estimated from ground surveys in 2004 and sample branches in 2005.

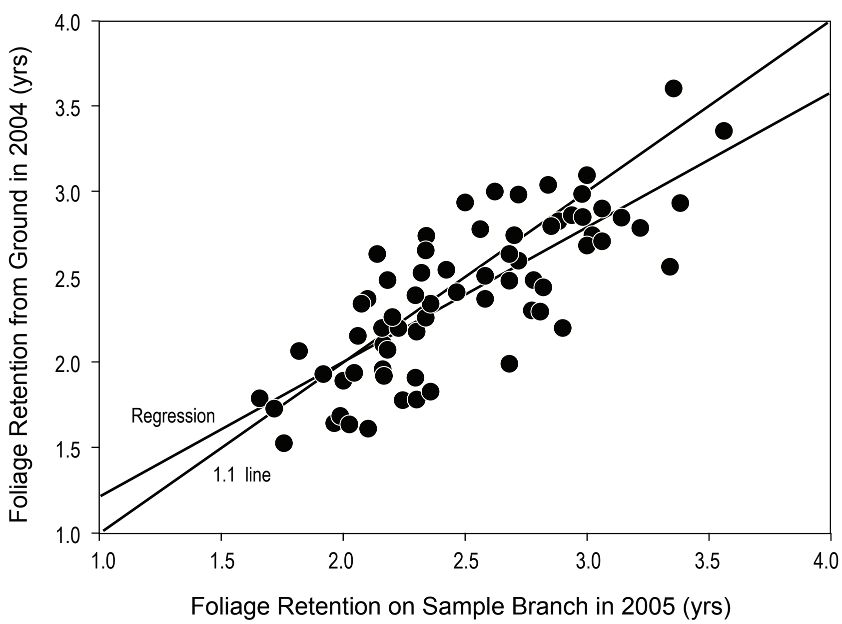

Figure 2. Relationship between foliage retention estimated from ground surveys in 2004 and sample branches in 2005 for Growth Impact Study plots only.

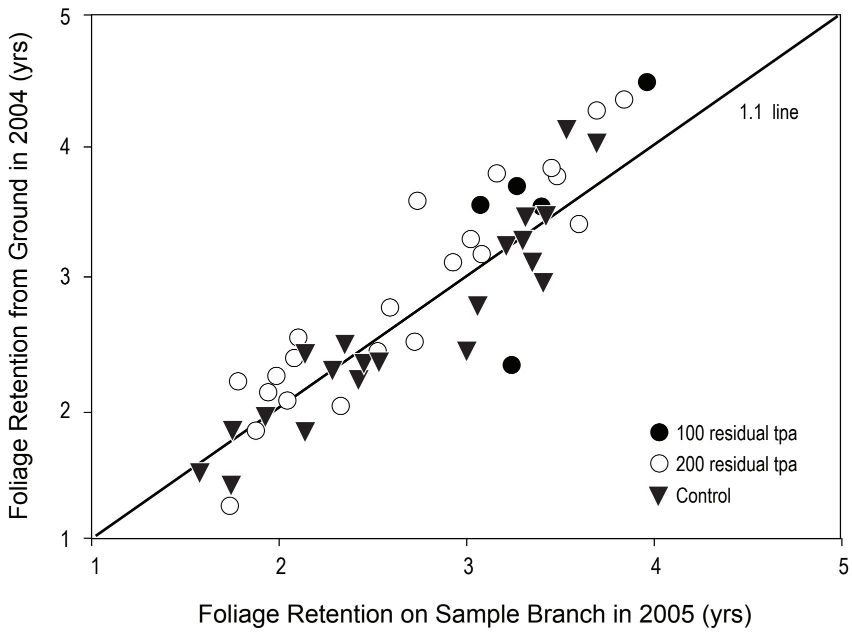

Figure 3. Relationship between foliage retention estimated from ground surveys in 2004 and sample branches in 2005 for control and thinned plots in the Pre-Commercial Thinning study.

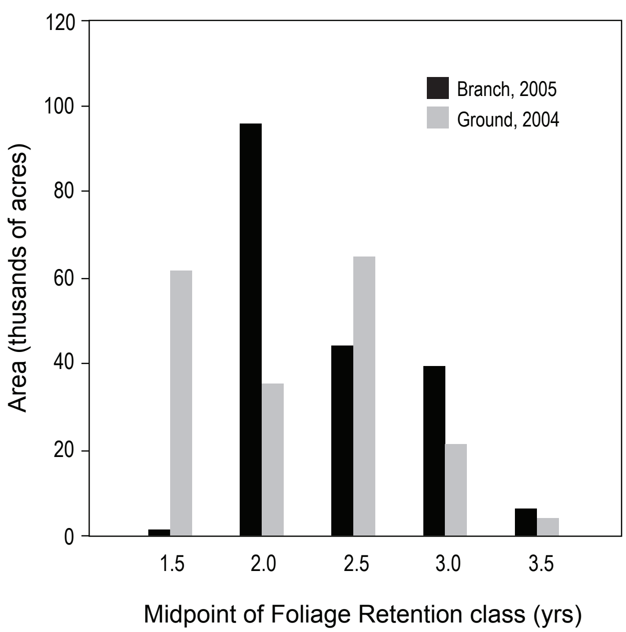

Figure 4. Estimated distribution of acreage by SNC severity class, based on GIS plots. Target population was 187,545 acres of 10-30-yr old (1998) plantations in north coastal Oregon.

The sampled population of 10-20-yr-old plantations in 1998 covered 187,545 acres in north coastal Oregon. The estimated distribution of these acres by foliage retention class differed considerably between the two years and estimation procedures (Figure 4). The ground-based sample for 2004 suggests approximately 60,000 acres more in the 1.5-yr class than the branch-based sample for 2005, and approximately 60,000 acres fewer in the 2.0-yr retention class.

Laboratory work on the sampled branches continues, but estimation of foliage mass by age class is nearing completion. Pseudothecia counts will begin after separation and weighing of foliage is completed, and the results will be compared to those from branches sampled at the same locations in spring 1997.

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Response in Douglas-fir Leaf Area Index and Litterfall Dynamics to Swiss Needle Cast in North Coastal Oregon

Aaron Weiskittel, Doug Maguire

Abstract

The relationship between leaf area index (LAI; m^2 m^{-2}; total one-sided), its seasonal variation, and the level of stand defoliation has not been well quantified despite its importance for growth forecasts in regions with stand health issues. The influence of Swiss needle cast (SNC) on Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco) LAI and litterfall dynamics were quantified by destructively sampling 122 stems from 36 different permanent plots throughout north coastal Oregon and monitoring stand litterfall for 3 years in 15 of these plots. LAI, annual litterfall turnover, and its seasonal distribution were all influenced by plot physiographic features and the degree of SNC severity. Mean LAI in this study was 5.44 ± 2.16, indicating that SNC, the use of direct measurements, and sampling throughout the growing season led to significantly lower values than previously published for the region. For a given stand structure and level of SNC, LAI varied by 25% from the dormant season to maximal leaf area, on average. The proportion of LAI annually turnovered was not constant and depended on dormant season LAI. SNC also influenced when the litterfall occurred as a greater proportion of foliage turnover occurred earlier in the spring with increasing disease severity. The effects of the disease on fine woody material litterfall, on the other hand, were depended on plot aspect. Overall, the results suggest that defoliation can drastically reduce LAI and its annual turnover rate and seasonal distribution.

Introduction

Leaf area index (LAI; m^2 m^{-2}; total one-sided) has long been one of the most important plant canopy attributes for determining potential net primary production (Russell et al. 1989). Several recent reviews highlight the continued interest in this variable and techniques for estimating it more accurately (Bréda 2003; Jonckheere et al. 2004; Weiss et al. 2004). LAI drives the within- and the below-canopy microclimate, determines and controls canopy water interception, radiation extinction, transpiration, and carbon gas exchange (Bréda 2003). Hence, several process-based models of canopy processes such as 3-PG (Esprey et al. 2004), Soil-Plant-Atmosphere (Licata 2003), MAESTRO (Luo et al. 2001), and BGC (White et al. 2000) are very sensitive to this variable. For example, Licata (2003) found that increasing the value of LAI from the reference value minus 50% to the reference value plus 50% caused an increase in gross primary production of 44% using the SPA model. Accurate estimation of LAI is often limited by the tedium of collecting samples (direct estimation) and difficulties in separating leaves from branch and stems (indirect estimation), particularly in stands that have been partially defoliated (Kucharik et al. 1998). Hence, relatively little is known about how much LAI changes in response to annual and seasonal fluctuations in stand health, which limits the use of process-based models to predict growth under changing stand conditions.

While improved modeling of LAI may significantly increase process-based model precision, other factors such as carbon allocation and storage and leaf area development and senescence might be equally important (Ewert 2004). Modeling the seasonal dynamics in coniferous stand LAI, however, has received relatively little attention. Seasonal variation in stand LAI can be relatively large and is related to species-specific differences in foliar longevity (Vose et al. 1994). Stand LAI in a 32-year-old eastern white pine (*Pinus strobus* L.) plantation ranged from 3.5 in the dormant season to a maximum of 5.3 in late July (Vose and Swank 1990). A similar trend has been reported for a young, widely spaced *Pinus radiata* plantation in New Zealand (Whitehead et al. 1994). Our understanding of the seasonal variation in stand LAI is based on only a few *Pinus* species and limited environmental conditions, so further investigation is warranted (Vose et al. 1994).

The amount of stand LAI turnover annually is also quite variable and is controlled by several environmental factors. Although numerous studies have quantified average litterfall rates across a range of species and stand conditions (Bray and Gorham 1964), few models exist for predicting litterfall (Lehtonen et al. 2004; Muukkonen and Lehtonen 2004). Modeling annual litterfall is also limited by insufficient data and high variability, which often limits simple relationships between stand characteristics and annual turnover (Ranger et al. 2003). Further, the influence of stand health on litterfall rates has not been clearly established. For example, some studies have found no correlation between defoliation and litterfall (Bille-Hansen and Hansen 2001; Poikolainen and Kubin 1997), while other studies have documented a positive correlation (Arkley and Glauser 1980; Jukola-Sulonen et al. 1995). A predictive model of annual LAI turnover, however, is important for predicting litter input to soil and ultimately the size of soil carbon pools (Lehtonen et al. 2004). The assumed 20-25% annual turnover rate of leaf area in mechanistic growth models for Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco) has significant implications for growth predictions in these models (Mohren 1987; Bartelink 2000; Licata 2003).

Currently, over 72,000 ha of Douglas-fir plantations in the Oregon Coast Range are showing symptoms of the Swiss needle cast (SNC) disease, reflecting the dramatic increase of this disease in recent years. The disease has reduced tree vigor and caused premature needle abscission (Manter et al. 2003a). This has significantly altered several crown structural attributes (Weiskittel 2003) and led to average volume growth losses as high as 52% in severely affected plantations (Maguire et al. 2002). Growth losses presumably result from both reduced LAI (Weiskittel 2003) and disruption of gas exchange in surviving needles (Manter et al. 2003a). Better understanding of the disease's influence on LAI may improve predictions of growth losses. Moreover, differences in LAI imposed by SNC provides an opportunity to model monthly and annual LAI turnover across a range of initial LAI.

The goal of this analysis was to test and quantify the relationship between SNC, LAI, and leaf area litterfall dynamics. In addition, the influences of age, stand density, site topographic features (i.e. aspect, elevation, and slope), and other factors were also assessed in the course of isolating the effects of SNC. The specific objectives were to test the following three null hypotheses: (1) LAI is invariant across SNC severity; (2) annual turnover of LAI is invariant across SNC severity; and (3) monthly distribution of LAI turnover is invariant across SNC severity. The disease was expected to cause a decrease in standing LAI, an increase in LAI turnover rate, and a shift in the seasonal distribution of LAI turnover from late fall to the late spring/early summer.

Methods

Study sites

All plots were located in the Oregon Coast Range; within 32 km of the Pacific Ocean, north of Newport, Oregon (N44°40', W124°4') and south of Astoria, Oregon (N46°7', W123°45'). The climate in this study area is humid oceanic, with a distinct dry summer and a cool, wet winter. Rainfall varies from approximately 180 to 300 cm year^{-1}, and January mean minimum and July mean maximum temperatures range from –2 to 2°C and from 20 to 28°C, respectively. Variation in precipitation and temperature for this area is strongly correlated with elevation and proximity to the coast. Elevation ranged from 45 to 550 m and all aspects were represented in this study.

The sampled plantations were 10- to 60-years old at breast height and contained ≥75% Douglas-fir by basal area, with varying amounts of naturally regenerated western hemlock (Tsuga heterophylla (Raf.) Sarg.) and other conifer and hardwood species (Table 1). Twenty-eight stands in total were sampled for this study and were systematically chosen to represent a range of SNC severity.

Table 1. Attributes of the plots sampled in 2002-2005 for LAI determination and litterfall dynamics.

Attribute	*Mean*	*Standard deviation*	*Minimum*	*Maximum*
	direct LAI determination (n = 36)			
Total basal area (m^2 ha^{-1})	37.89	15.39	10.45	76.83
Douglas-fir quadratic mean diameter (cm)	29.95	10.66	11.41	53.49
Trees per ha	663.33	372.69	175.00	1790.75
Average breast-height age (year)	28.82	13.97	11.00	60.70
Site index (Bruce (1981); height at 50 years breast height, in m)	39.39	4.15	26.63	46.20
LAI (m^2 m^{-2}; one-sided)	5.45	2.16	2.28	11.24
Foliage retention (years)	2.58	0.81	1.56	4.39
	litterfall dynamics (n = 15)			
Total basal area (m^2 ha^{-1})	35.87	9.12	21.29	49.18
Douglas-fir quadratic mean diameter (cm)	28.73	4.08	21.70	37.68
Trees per ha	668.14	267.33	271.70	1235.00
Average breast-height age (year)	24.56	2.75	18.30	29.80
Site index (; height at 50 years breast height, in m)	39.29	1.51	37.51	41.16
LAI (m^2 m^{-1}; one-sided)	5.33	1.28	3.85	8.45
Foliage retention (years)	2.32	0.47	1.66	3.85

Data collection

Leaf area index

Sampling for leaf area index occurred in the spring prior to budbreak (2002 growing season) and fall of 2002 (2003 growing season; 10-30-yr plantations) as well as the winter of 2004 (2003 growing season; 30-60-yr-plantations). In each stand, 3-5 trees were felled and intensively measured. Before felling, diameter at breast height (DBH), total height (HT), height to crown base (HCB), and maximum crown width (CW) were measured (Table 2). After felling, the location and diameter of every living branch (>1 mm in diameter) was determined. Nine to fifteen branches (3-5 per crown third; 2-3 whorl and 1-2 interwhorl) were randomly selected and transported back to the laboratory for more intensive measurements. The sample branches were clipped into separate age classes, placed into smaller paper bags, and dried in an oven at a temperature of 85°C for three days. The needles were separated from the branch, and each component was weighed to the nearest 0.01 g. A subsample of foliage samples was taken for specific leaf area (SLA; cm^2 g^{-1}) determination and nutrient analysis.

Litterfall

To assess monthly and annual leaf area dynamics, twelve relatively young (10-30-yrs in age) stands were selected for intensive litterfall measurements. Within each stand's 0.08-ha plot, ten square 0.18 m^2 litterfall traps were systematically placed 3 m apart and 3 m from the plot edge. The traps were established in April 2002 and were collected monthly for the first year and at least three times a year in the next two years. The litterfall was dried at 85°C for 48 hours and separated into several different components including: (1) Douglas-fir foliage; (2) Douglas-fir woody material; (3) hardwood foliage; (4) western hemlock and other conifer foliage; and (5) other materials such as fruits, bud scales, and cones. A subsample from each collection period's litterfall was taken for SLA determination and nutrient analysis.

Plot measurements

SNC severity on each of the young plantation study sites has been recorded every year since 1996 by the Oregon Department of Forestry. The square 0.08-ha permanent plots were established in 1998 and on each plot, all trees were tagged at breast height and measured for DBH, HT, and height to crown base (HCB). These measurements were repeated in 2000, 2002, and 2004. Ten trees on each plot have been scored for SNC every year. On these trees, the crown was divided vertically into thirds, the average number of years that foliage was retained in each third was estimated visually to the nearest 0.1 year, and tree average was computed as a simple mean. Overall crown discoloration was rated on a 1 to 4 scale with 1 being highly discolored. Plot ratings were computed as the average of all ten trees. For the older plantations, two square 0.2-ha permanent plots (control + thinned) were established within each stand during 2001 and all trees were tagged at breast height and measured for DBH, HT, and HCB. These measurements were repeated in 2003. Five trees on each plot have been scored for SNC every year starting in 2001. Due to the heights of crowns and associated visibility problems in these older, larger trees, a single average rating was given for the whole crown. Two breast-height cores were taken perpendicular to slope from each tree and used to compute sapwood area. The sapwood area at crown base was estimated using a previously constructed sapwood taper equation for Douglas-fir . Crown sparseness (CLSA) was computed as the ratio of crown length (CL; cm) to sapwood area at crown base (cm^2). Plot ratings were computed as the average of all five trees.

Data analysis

Various linear and nonlinear regression models were fitted to the data to develop equations for estimating stand-level LAI and foliage dynamics. Final models were chosen on the basis of residual analysis, Akaike's information criterion (AIC) and biological interpretability. All analyses were done in SAS v8.2 (SAS Institute, Cary, NC) and S-PLUS v6.2 (Mathsoft, Seattle, WA).

The data had a distinct hierarchical structure (multiple measurements within plots within years) and as a result, violated the assumption of independence and zero correlation. A multi-level, mixed-model analysis was therefore employed. When heteroskedasticity was detected in the residual plots, the final equation was weighted by a power variance function of the primary independent variable. Likelihood ratio tests were used to compare nested model forms.

Leaf area index

Plot-specific branch- and tree-level equations for estimating leaf area were developed. Tree leaf area (m^2) was estimated for all plot trees using a procedure similar to the one outlined by Robinson and Wykoff (2004) for estimating missing heights using mixed-models. Basically, a global model was fitted to the entire dataset, each plot's random coefficient was extracted, and the parameters were updated accordingly. Several different model forms were presented and the best was similar in form to the one presented in Maguire and Bennett (1996):

$$[1] \quad TLA = 0.9839 * CL^{1.322+\delta_1+\phi_1} * \exp(0.8752 + \delta_2 + \phi_2 * \frac{DBH}{HT})$$

where TLA is tree leaf area (m^2), δ_i is a random parameter for year (i = 2002, 2003, 2004), and ϕ_i is a random parameter for each plot. LAI was calculated by summing the predicted tree leaf areas and dividing by the plot area. Standing LAI was modeled with the following equation:

$$[2] \quad LAI = \beta_{20} + \delta_{21} + \beta_{21}TPH_{DF} + \beta_{22}RD_{DF} + \beta_{23}AGE + \beta_{24}CLSA_{PLOT} + \beta_{25}FOLRET + \beta_{26}LAI_{MAX}$$

where TPH_{DF} is Douglas-fir stems per ha, RD_{DF} is Douglas-fir stand relative density (Curtis 1982), $CLSA_{PLOT}$ is the plot mean crown sparseness (Maguire and Kanaskie 2002), FOLRET is plot mean foliage retention (years), and LAI_{MAX} is an indicator variable for sampling during maximal leaf area (1 if LAI value is from fall of 2002, 0 otherwise).

Litterfall

Size

The amount of LAI lost as litterfall was calculated during each collection period as the mass average of the ten traps multiplied by its determined SLA and divided by the trap area. For periods with a missing SLA measurement, the plot's overall mean SLA was used. The effects of SNC on litter SLA and its changes through the various seasons were modeled as linear function of several stand variables:

$$[3] \quad SLA = \beta_{30} + \beta_{31}BA + \beta_{32} * ASP12 + \beta_{33} * COAST + \beta_{34} * FOLRET + \beta_{35} * JDATE$$
$$\beta_{36} * \ln(JDATE) + \beta_{37} * (COAST * FOLRET)$$

where BA is stand basal area($m^2\ ha^{-1}$), ASP12 is cosine transformation of slope and aspect (Stage 1976), COAST is the plot distance from the Pacific Ocean (km), and JDATE is Julian date.

Amount

The proportion of LAI annually turned over was first modeled by several different linear and nonlinear functions of dormant season LAI. Since LAI wasn't measured for each collection period, a more general equation using stand-level variables and SNC severity was developed with the following form:

$$[4] \quad LAI_T = \exp(\beta_{40} + \delta_{40} + \beta_{41}AGE + \beta_{42}DQ_{DF} + \beta_{43}SINA + \beta_{44}ASP22 + \beta_{45}FOLRET + \beta_{46}CLSA_{PLOT})$$

where LAI_T is the annual LAI turnover rate, DQ_{DF} is Douglas-fir stand quadratic mean diameter (cm), SINA is the sine transformation of aspect (Stage 1976), and ASP22 is the sine transformation of slope and aspect (Stage 1976).

The amount of fine woody material annual turnover rate was also modeled as function of several stand-level variables. The final equation had the following form:

$$[5]\quad \ln(WOD_{LIT}) = \beta_{50} + \beta_{51}AGE + \beta_{52}TPH + \beta_{53}COSA + \beta_{54}FOLRET + \beta_{55}CLSA_{PLOT}$$

where WOD_{LIT} is annual fine woody material litterfall rate (kg ha^{-1}), TPH is trees per ha, and COSA is the cosine transformation of aspect (Stage 1976).

Seasonal distribution

To estimate the distribution of LAI turnover during the growing season, the date of first bud flush was first estimated for each plot using the approach outlined in Thomson and Moncrieff (1982) and Daymet generated daily climate (http://www.daymet.org). For each litterfall collection period, the number of days since bud flush and the cumulative amount of LAI turnovered were calculated. A logistic equation was fitted to the data::

$$[6]\quad CM\_LAI_T = \frac{1}{1+\exp(\beta_{60} + \beta_{61}DSBF + \beta_{62}*ELEV + \beta_{63}COSA + \beta_{64}CLSA_{PLOT})}$$

where CM_LAI_T is the cumulative proportion of LAI turnovered, DSBF is the number of days since bud flush, and ELEV is plot elevation above sea level (m). The seasonal distribution of fine woody material turnover was modeled using a similar approach. The final model had the following form:

$$[7]\quad CM\_WOD_T = \frac{1}{1+\exp(\beta_{70} + \beta_{71}DSBF + \beta_{72}*ELEV + \beta_{73}SINA + \beta_{74}FOLRET + \beta_{75}(SINA*FOLRET))}$$

where CM_WOD_T is the cumulative proportion of fine woody material turnovered (kg ha^{-1}) and all other variables have been defined above.

Results

Leaf area index

Douglas-fir mean stand LAI was 5.44 ± 2.16 and ranged from 2.29 to 11.25 (Figure 1). Within-year variability was significantly greater than between-year variability as it comprised nearly 67% of the original variation in LAI. A model containing both $CLSA_{PLOT}$ and foliage retention did not perform significantly better than one containing just foliage retention (p = 0.127). In addition, no transformation of Julian date provided a better fit to the data than the simple indicator variable for maximal leaf area. Overall, LAI significantly increased with RD_{DF} (p<0.0001) and FOLRET (p<0.0001), while it decreased with TPH_{DF} (p = 0.045) and AGE (p<0.0001; Table 2). Although a random parameter for year significantly improved model fit (p = 0.0104), there was very little variation between years after accounting for maximal leaf area, stand structure, and SNC severity (~1%). For a given stand structure and year, LAI in a stand with high SNC (FOLRET = 1.5) was reduced by 30.9% when compared to a stand with low SNC (FOLRET = 3.5). LAI varied by 25.1% in a given year between dormant season and maximal leaf area. There was no significant difference for LAI sampling in the spring prior to budbreak and in the early winter (p = 0.5639).

Litter fall

Size

Mean litterfall SLA was 56.8 ± 5.13 cm^2 g^{-1} and ranged from 47.4 to 77.6 cm^2 g^{-1}. In the final model, foliage retention and its interaction with distance from the coast were not significant. While this indicates that SNC had no impact on litter SLA, the combination of aspect, slope, and distance from the coast are each well correlated with SNC severity as it tends to increases on southern aspects and distance from the coast. Litterfall SLA increased as plots become steeper and more southerly (p<0.0001), while it decreased with distance from the coast (p<0.0001) and Julian date (p = 0.0002). This would imply that litterfall SLA would increase as SNC severity was greater (Figure 2). Litterfall SLA peaked in the late fall/early winter.

Amount

Mean annual LAI turnover was 1.44 ± 0.46 and ranged from 0.52 to 2.75 (Figure 2). Expressed as a proportion of the measured dormant season LAI, annual LAI turnover was 0.34 ± 0.10 and ranged from 0.13 to 0.53 (Figure 3). This value was best modeled as a power function of initial LAI:

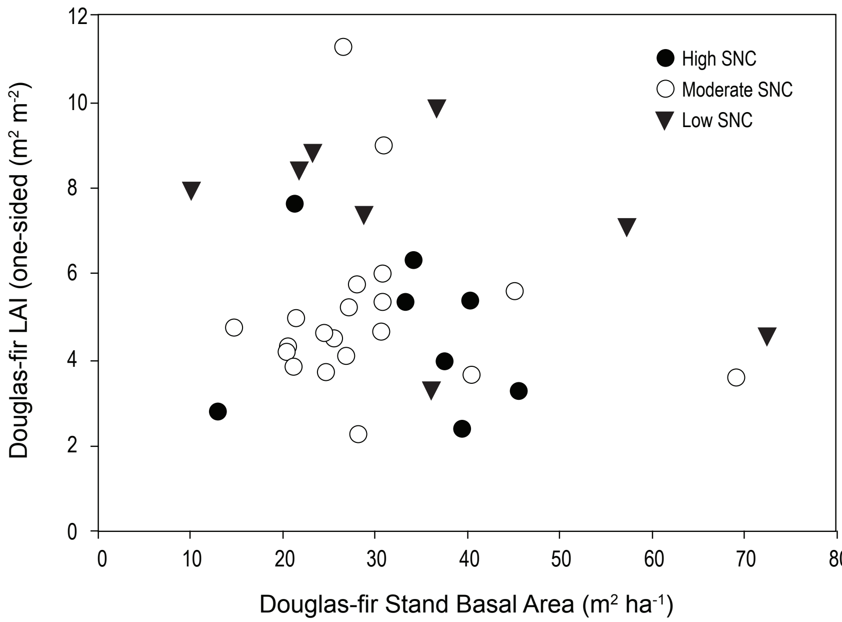

Figure 1. Plot of Douglas-fir LAI (one-sided m^2 m^{-2}) versus Douglas-fir stand basal area (m^2 ha^{-1}) by SNC severity class. High SNC is considered a plot with mean foliage retention less than 2 years and low SNC has a mean foliage retention greater than 3.

$$[8] \quad \frac{LAI_T}{LAI_D} = 1.3074 * LAI_D^{-0.8166}$$

where LAI_D is dormant season LAI. The equation had a R^2 of 0.33 and a residual stand error of 0.11. Unlike standing LAI, the within-year variability of annual LAI turnover was nearly equal to the between-year variability. For a given stand, there was a significant difference in LAI_T between years ($p<0.0001$) with 2002 having the highest turnover. Between year differences in LAI_T for a given stand structure and level of SNC severity averaged 0.3 ± 0.2 and was as high as 0.5 in this study. LAI_T significantly increased with Douglas-fir quadratic mean diameter ($p<0.0001$) and north-easterly aspects ($p<0.0001$), while it decreased with mean breast-height age ($p<0.0001$) and foliage retention ($p<0.0001$). For a given year and stand structure, a stand with low SNC (FOLRET = 3.5) had a mean LAI_T 51.2% lower than a stand with high SNC (FOLRET =1. 5).

Mean fine woody annual litterfall was 578.4 ± 333.6 kg ha^{-1} and ranged from 84.4 to 1505.0 kg ha^{-1} (Figure 4). In comparison to foliage litterfall, there was relatively little annual variation in fine woody lit-

Table 2. Final equation form, R^2, and residual standard error (RSE) for equations presented in this study.

Model	***Equation form***	***R^2***	***RSE***
2, standing LAI	$LAI = \exp(1.3433 - 0.0004 * TPH_{DF} + 0.1132 * RD_{DF} - 0.0239 * AGE + 0.1849 * FOLRET + 0.2886 * LAI_{MAX})$	0.74	1.23
3, litterfall SLA	$SLA = 4.4244 - 0.0045 * BA + 0.0924 * ASP12 - 0.0067 * COAST + 0.0005 * JDATE - 0.0491 * \ln(JDATE)$	0.29	0.08
4, LAI turnover	$LAI_T = \exp(2.4851 - 0.1096 * AGE + 0.0472 * DQ_{DF} + 0.1997 * SINA + 0.3106 * ASP22 - 0.3589 * FOLRET)$	0.45	0.01
5, fine woody material turnover	$\ln(WOD_{LIT}) = 6.0369 + 0.0422 * AGE + 0.0005 * TPH - 0.0474 * COSA - 0.5043 * FOLRET$	0.32	0.55
6, seasonal distribution of LAI_T	$CM\_LAI_T = \frac{1}{1 + \exp(4.0716 - 0.0214 * DSBF - 0.2508 * ELEV - 0.0086 * COSA - 0.1093 * CLSA_{PLOT})}$	0.96	0.07
7,seasonal distribution of woody turnover	$CM\_WOD_T = \frac{1}{1 + \exp(8.3929 - 0.0234 * DSBF - 0.0209 * ELEV + 3.3041 * SINA - 0.9428 * FOLRET - 1.2030 * (SINA * FOLRET))}$	0.93	0.09

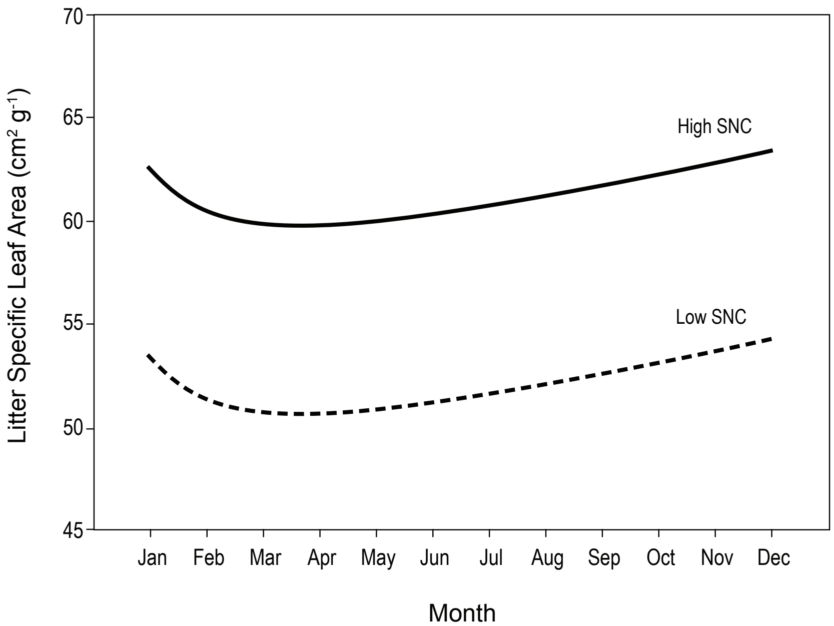

Figure 2. Predicted litter specific leaf area (cm^2 g^{-1}) by month and SNC severity. The level of SNC was estimated based on physiographic features with high SNC located on a southern aspect and 5 km from the coast, while low SNC was located on a northeasterly aspect and 25 km from the coast.

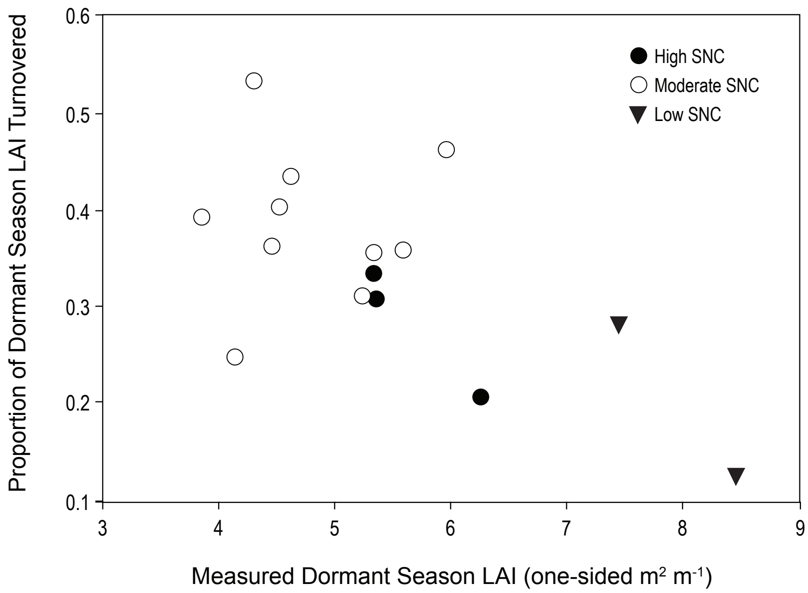

Figure 3. Annual Douglas-fir LAI (one-sided m^2 m^{-2}) versus Douglas-fir stand basal area (m^2 ha^{-1}) by SNC severity class.

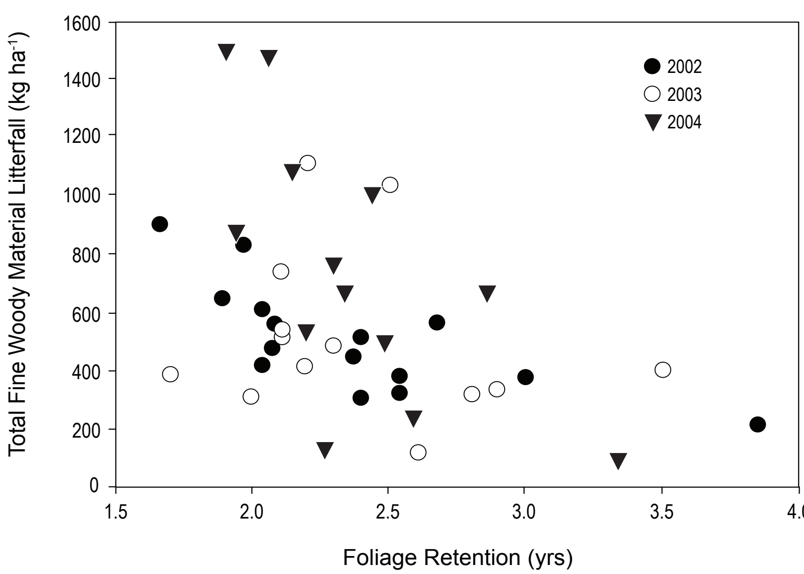

Figure 4. Annual Douglas-fir fine woody material litterfall (kg ha^{-1}) versus plot mean foliage retention by year.

terfall rates. A significant difference in mean fine woody litterfall, however, existed between 2002 and 2004 ($p = 0.0285$) with the mean rate being 39.3% higher in 2004. Fine woody annual litterfall rate significantly increased with stand mean breast height age ($p = 0.0256$), the number of stems per ha ($p = 0.0043$), and more northeasterly aspects ($p = 0.0060$), while it decreased with foliage retention ($p = 0.0069$). For a given stand structure, the fine woody material litterfall rate was 44.8% lower in a stand with low SNC when compared to one with severe SNC.

Seasonal distribution

LAI_T showed a clear seasonal trend with a peak in the early fall regardless of SNC level. On average, nearly 50% of LAI_T occurred between October and December. SNC had a significant influence on the seasonal distribution of LAI_T as indicated by the plot mean crown sparseness index ($p = 0.0048$). LAI_T peaked sooner after first bud flush as the stand elevation increased ($p<0.0001$), the aspect became more northerly ($p<0.0001$), and SNC severity increased (Figure 5).

The turnover of fine woody material also showed a season trend with a peak in the early winter regardless of SNC level. Nearly 52% of the turnover of fine woody material occurred between December and February. SNC had a significant influence on the seasonal distribution of fine woody material turnover as indicated by foliage retention ($p < 0.0001$), but the relationship was influenced significantly by plot aspect ($p <0.0001$). On southern aspects, the seasonal distribution of fine woody material turnover peaked earlier as SNC severity decreased and plot elevation increased ($p<0.0001$). On northern aspects, there was relatively little difference in the seasonal distribution of fine woody material turnover. (Figure 6).

Discussion

Defoliation is a highly dynamic and variable process that can significantly modify several critical ecosystem attributes such as decomposition rates, soil temperature and moisture, and susceptibility to further disturbance. These changes are a direct result of the loss of foliage, but estimating the actual reduction in LAI due to defoliation is difficult because of inherent annual and seasonal variation. In the northern coast range of Oregon, SNC has dramatically altered both LAI and the annual and seasonal turnover of leaf area. LAI in this study averaged near 5.5 and when compared to a healthy stand, was reduced by 31%. Litterfall rates were more variable than LAI, but also showed a significant relationship with SNC. Compared to a healthy stand, foliage and fine woody material litterfall rates were nearly 52 and 45% greater in stands with high SNC, respectively. The disease has also altered the timing of litterfall as a greater proportion of the foliage litterfall occurs earlier in the growing season than normal. An opposite trend was found for the seasonal distribution of fine woody material litterfall as it wasn't drastically influenced by SNC or in some cases, occurred later in the growing season than normal, depending on plot aspect. These changes have important implications for nutrient-cycling and future productivity of these plantations.

Leaf area index

LAI has often been shown to increase with enhanced nutrition (Balster and Marshall 2000), greater water availability (Grier and Running 1977), increased age up to a steady-state at 5 to 20 yrs (Kull and Tulva 2000), and more stand basal area (Gholz 1982). Turner and Long (1975), however, report that Douglas-fir stands do not reach an LAI plateau until age 40-60 yrs. LAI in

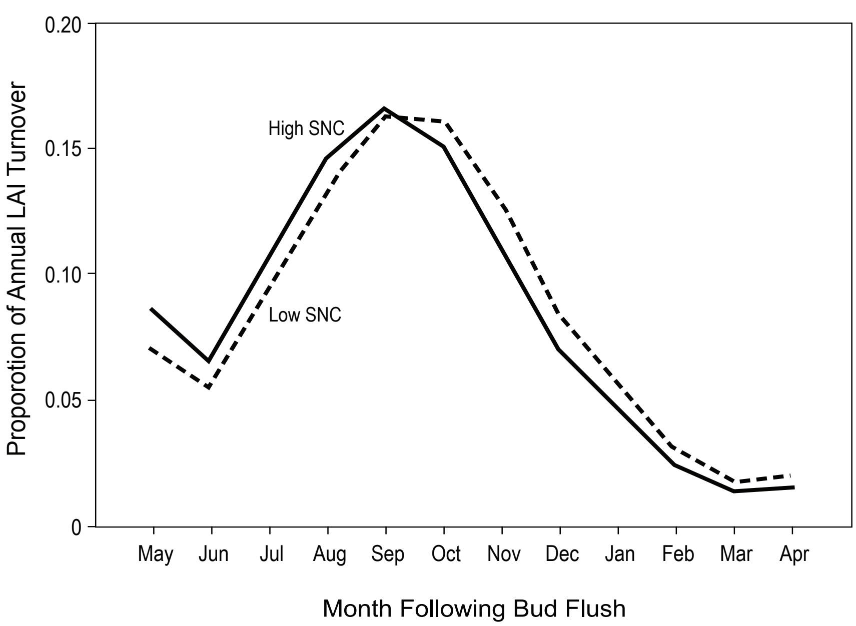

Figure 5. Monthly distribution of LAI turnover by SNC severity. Date of first bud flush was assumed to be May 1, while high and low SNC were associated with $CLSA_{PLOT}$ of 7.5 and 5.5, respectively.

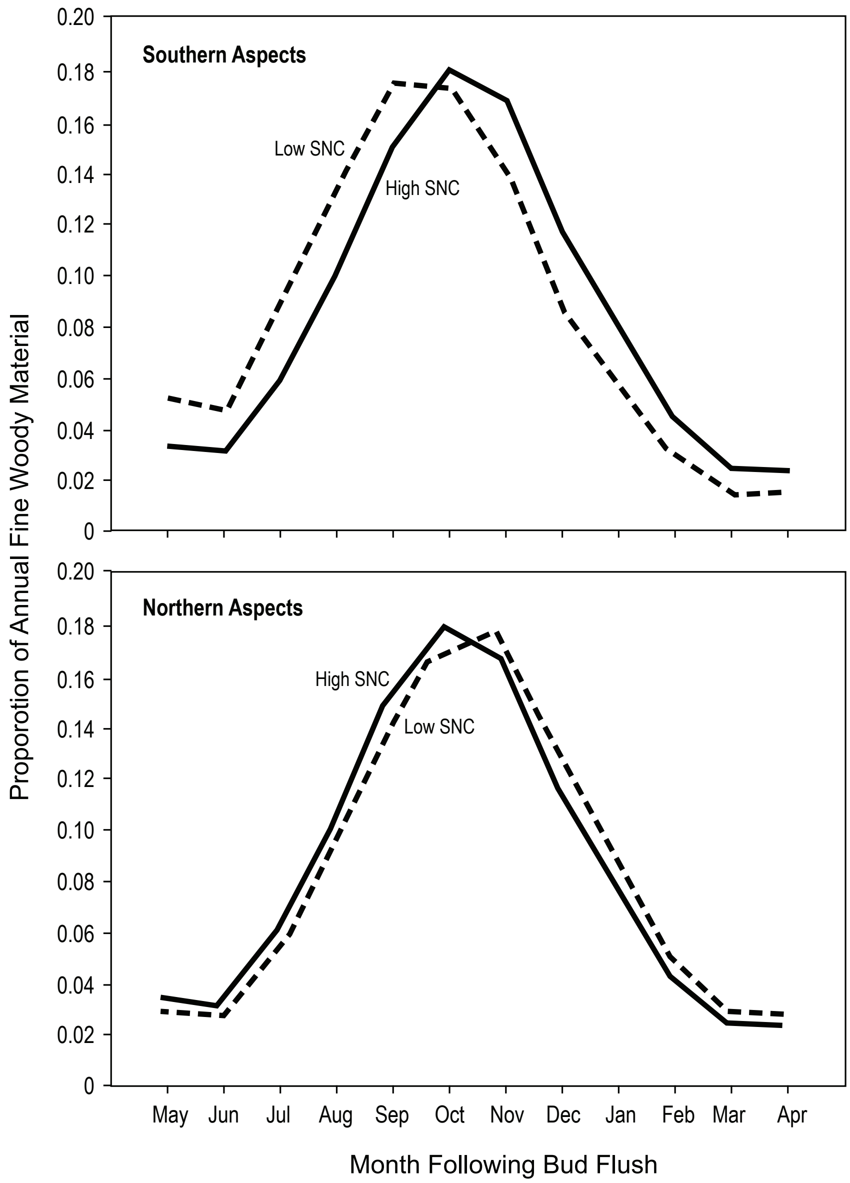

Figure 6. Monthly distribution of fine woody material by SNC severity and plot aspect.

this study increased with Douglas-fir stand relative density, but decreased with both trees per ha and mean breast-height age. This effectively limits generalizations regarding LAI, stand density, and age. This is mostly likely a reflection of the varied management history of these stands as more than half of them received a pre-commercial thinning treatment of varying intensity. The mean reduction in LAI due to SNC was 1.9. Similar, but less drastic, reductions in stand LAI have also been reported in response to climatic disturbances such as wind and ice storms (Grier 1988; Thomas and Winner 2000).

Mean LAI was 5.5 in this study, which is much lower than previously published values for Douglas-fir as LAI has generally ranged between 4.0 and 11.0, with a mean around 7.5 (Marshall and Waring 1986; Thomas and Winner 2000; Turner et al. 2000). These differences may be attributable to site conditions and methodology. Most of these studies have taken place in the Cascades rather than near the coast. Secondly, most of the Pacific Northwest studies have estimated LAI using optical techniques, which consistently underestimate LAI because of the aggregation of needles within crowns and canopies (Marshall and Waring 1986). Estimated LAIs, however, were close to levels reported in young Douglas-fir plantations that had been intensively managed similar to several stands in this study (Velazquez-Martinez et al. 1992). In addition, the seasonal variability in LAI was remarkably similar to previously published values of 25% (e.g. Vose and Swank 1990; Whitehead et al. 1990; Bosveld and Bouten 2001).

Litterfall

Size

Few studies have reported the SLA of needles in foliage litter, nor its seasonal variation (Roberts et al. 1999), despite the fact that litter SLA is a good predictor of the rate of decomposition (Lambers et al. 1998). Litter SLA is usually very similar in many respects to living foliage (Roberts et al. 1999), but has a definite seasonal pattern because of foliage dynamics and translocation patterns within the canopy (Piene and Fleming 1996). Roberts et al. (1999) and Bouriaud et al. (2003) found a wide range of SLA occurs in the litter throughout the year, but SLA was generally highest in the early fall due to the larger contribution of foliage from the bottom of the canopy to the litter. As the year progresses, foliage with smaller SLA from the upper canopy contributed substantially more to the litter (Roberts et al. 1999). Piene and Fleming (1996) found that age-specific rates of needlefall tend to increase with needle age, particularly in the lower crown.

Although no direct measures of SNC severity were significantly related to litter SLA, the combination of slope, aspect, and distance from the coast suggest that litter SLA increased with greater SNC levels. This is mostly likely a result of the disease significantly altering foliage age distribution and age class dynamics. SNC has resulted in a higher foliage turnover rate, a greater proportion of the younger age classes, and on average, a greater SLA (Weiskittel 2003). This higher SLA is due to the fact that the younger needles are flatter and less dense. The greater litter SLA with increasing SNC results from the loss of these young, high SLA needles. SNC altered the seasonal trend in litter SLA by altering the crown position where the needle loss is occurring. Manter et al. (2003b) found consistently higher fungal colonization and more severe symptoms in the upper portions of the crown, implying that a greater proportion of the litter in a severe SNC site comes from the upper canopy. The positive correlation between rate of litter decomposition and litter SLA (Lambers et al. 1998) suggests that decomposition may increase with greater SNC, especially when considering the compounding SNC effects on forest floor temperature and moisture. SNC and the responses it stimulates therefore have important implications for nutrient-cycling within these stands.

Amount

Total litter production increases with age due to the increasing input of woody material, while foliage litterfall remains constant after age 40 (Gessel and Turner 1976). Several factors beside age influence litterfall rates including stand spacing (Piene and Fleming 1996), site quality (Maguire 1994), species composition, and latitude (Albrektson 1988). Climate plays a particularly important role; for example Kouki and Hokkanen (1992) observed a strong positive correlation between needle litterfall and mean July temperature with high temperatures. Conversely, Dimock (1958) found that unseasonably low fall temperature nearly tripled the amount of litter that was dropped during the ensuing year. Thus, even within a stand, litterfall rates can vary substantially year to year, which was also found in this study.

Foliage litterfall increased with Douglas-fir quadratic mean diameter in this study, but decreased with age. Similary, Piene and Fleming (1996) noted that spacing affects many aspects of needlefall including timing and annual variation. In their work, the unspaced or higher density plots had a significantly lower needle lifespan, implying that greater needlefall rates are expected at greater stand densities, which is similar to this study. Trofymow et al. (1991) and Turnbull and Madden (1983) similarly found a positive correlation between litterfall rates and stand basal area, although Trofymow et al. (1991) noted that litterfall rates correlated poorly with stand density index. The decrease with age is mostly a reflection of the limited age range examined in this study (~10-30 yrs.). The influence of aspect on litterfall rates has not been previously described. Needle litterfall rates in this study decreased as aspect became more northeasterly. This may be related to the greater basal growth on southerly aspects (Stage 1976), lack of water stress on northerly aspects, or both. Previous studies have noted a positive correlation between stemwood increment and litterfall rates (Trofymow et al. 1991; Turnbull and Madden 1983). In this study, however, aspect likely indicated the additional effects of SNC on litterfall rates. Manter et al. (2003b) found that trees on south slopes had higher SNC fungal colonization and more severe symptoms when compared to north slopes.

Bray and Gorham (1964) noted that, in general, leaf material contributes 60-76% of the annual litter, while branches comprised 12-15%. For the most part, the litterfall composition of the plots examined in this study fell within these ranges. However, plots with greater retention tended to have a greater proportion of needlefall because of crown recession was relatively slower on these plots. In Pacific Northwest Douglas-fir stands, varying in age from 22 to 450 years, Gessel and Turner (1976) found that total annual litterfall ranged from 1,300 to 6,138 kg ha^{-1}. For a 43-year-old Douglas-fir stand located in the eastern Oregon Coast Range, Fogel and Hunt (1979) reported that total litterfall was 2,680 kg/ha and that almost 90% was foliage. Thinning has been shown to dramatically decrease litterfall rates for 8 to 15 years (Dimock 1958; Trofymow et al. 1991), but fertilization significantly increased the rate (Heilman and Gessel 1963; Trofymow et al. 1991). The mean litterfall rate found in this study when converted to a kg ha^{-1} basis (2433 ± 799 kg ha^{-1}) was similar to these previously published values.

Seasonal distribution

Both foliage and woody litterfall rates peak in the fall and early winter with the onset of strong, windy rain storms in the Pacific Northwest (Gessel and Turner 1976). Douglas-fir foliage litterfall generally peaks in October, with minimal litterfall occurring during the late winter and early spring (Dimock 1958; Gessel and Turner 1976; Fogel and Hunt 1979). Litterfall of fine woody material shows a less definite pattern but, like foliage litterfall, the majority of it tends to occur after winter storms with heavy wet snows or strong winds (Trofymow et al. 1991). While the general pattern observed in this study was similar to other studies, SNC, however, modified the seasonal distribution of foliage litterfall. Although most of the foliage litterfall occurred in the fall, a significant amount of foliage fell in the summer, which follows the biological lifecycle of the SNC-causing fungus, *Phaeocryptopus gauemannii*. The SNC disease cycle begins in the spring when spores are released from the pseudothecia on the older diseased needles and are carried by the wind and rain to newly emerged needles (Hansen et al. 2000). The spores germinate on the new needles, enter the needles through the stomates, and reside in the intercellular spaces of the leaf tissue until pseudothecia ramify through the stomates and appear in the fall (Hansen et al. 2000). Needles are then shed, regardless of age, when about 50% of stomata are occupied. This generally occurs in the late spring and early summer, which coincides with the earlier peak in foliage litterfall for stands with severe SNC when compared to healthy stands found in this study.

Fine woody material litterfall still tended to occur primarily in the winter in this study, but showed a relationship with both SNC and aspect. On northern aspects, there was little difference in the seasonal distribution of fine woody material litterfall. On southern aspects, the peak in fine woody material litterfall tended to occur later in the year for plots with severe SNC than normal. The role of aspect and elevation in controlling the seasonal distribution of fine woody material emphasizes the importance of wind and climate as critical factors. The role of SNC on southern aspects, however, requires further investigation. The trend observed in this study may be a product of its limited timeframe (~1 yr) and the highly stochastic nature of litterfall.

Conclusions

LAI is an important canopy attribute and is an excellent predictor of stemwood production. Its response to extended stand-level defoliation has not been well documented. In addition, examination of its seasonal development for conifers other than *Pinus spp*. has been limited. This study examined the influence of defoliation caused by an endemic foliar pathogen on LAI and its seasonal development as well as its relationship with annual litterfall. For a given stand structure, LAI was found to be reduced by 31% on sites with severe SNC and change by a mean of 25% through the course of a year. Both foliage and fine woody material litterfall rates were increased by the disease, indicating a positive relationship between defoliation and litterfall. The disease has altered the timing of the litterfall as a greater amount of foliage litterfall on sites with high SNC tends to occur in the spring, which is related to the biological lifecycle of the disease. Seasonal distribution of fine woody litterfall shows a more complex relationship with SNC and requires further investigation. These changes, however, provide significant evidence that SNC may be altering several fundamental ecosystem processes such as decomposition and nutrient-cycling.

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Growth Response of Young Douglas-fir to Balanced Fertilization in Western Oregon

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Abstract

Sixteen study sites were installed in young Douglas-fir plantations exhibiting a range of SNC infection levels to test basal area and volume growth responses to N, NPK, and NPK plus micronutrient fertilization treatments. Using a basic randomized block with covariates regression model without any interactions, responses to all treatments were positive, for volume growth ranging from 6.4% for NPK to 10.5% for NPKplus. Addition of treatment interactions with initial foliar nitrogen % and initial foliage retention to the equation provided further clarification: growth response decreased as foliar N% increased and foliage retention decreased, becoming negative at extreme levels of both variables. These results, in combination with the previously found negative correlation between foliar N% and foliage retention would indicate that these treatments would not be advisable in SNC-infected stands.

Introduction

Since the early 1970s, many field trials have been implemented in western North America to assess the benefits of fertilizing Douglas-fir (Miller and Pienaar 1973, Miller and Fight 1979, Peterson et al. 1984, Heath and Chappell 1989, Stegemoeller and Chappell 1990). Douglas-fir responds, on average, positively to nitrogen fertilization (Peterson and Hazard 1990), but the magnitude of response depends on such factors as site productivity (Edmonds and Hsiang 1987, Miller et al 1989), site nutrient availability (Hopmans and Chappell 1994, Petersen et al. 1984), degree of crown closure (Barclay and Brix 1985, Stegemoeller and Chappell 1989), the combination of crown size and foliar density (Brix and Ebell 1969, Brix 1983), and species composition (Miller et al. 1986).

Although results of this research have motivated nitrogen fertilization of nearly 100,000 acres of timberland each year in Oregon since 1990, nutrient dynamics in intensively managed Douglas-fir plantations have been impacted by harvesting, site preparation, and other activities that remove biomass, change soil structure, enhance leaching, or promote volatization. These changes may very well lead to large shifts in relative availability of nutrients and to imbalances in various tree tissues that were not detectable after harvesting old growth or naturally regenerated second-growth. In fact, high nitrogen levels relative to the availability of other nutrients have been hypothesized to be partially responsible for the current Swiss needle cast (SNC) epidemic along the Pacific Northwest coast

(Perakis et al. 2005). Swiss needle cast (SNC) is a foliar disease caused by the endemic fungus *Phaeocryptopus gaeumannii.* Since 1990, SNC has caused significant growth losses, estimated at 43 million board feet in 1996 for 10-30 year old plantations in north coastal Oregon (Maguire et al. 2002). The theory that relatively high availability of nitrogen has facilitated the emergence of SNC is supported by the fact that free amino acids (FAA) serve as a primary nutritional source for many foliar fungi (Jennings 1995). Furthermore, FAAs increase when nitrogen is in excess (Nasholm and Ericsson 1990). When Douglas-fir trees with relatively low levels of foliar nitrogen are fertilized with isotopically-labeled urea, *P. gaeumannii* responds to the elevated nitrogen levels, with increased fungal fruiting, leading in turn to an increase in disease severity (El-Hajj et al. 2004). Because urea nitrogen fertilization continues to be the standard regime in second and third rotation plantations, its possible exacerbating effect on SNC has prompted reassessment of fertilization regimes (Talbert and Marshall 2005), particularly in regard to balanced nutrition among all macro and micronutrients.

Fertilization has been included in numerous studies investigating the ability of silvicultural treatments to ameliorate SNC. In one study, a diseased plantation received 200 lbs N/acre as urea at year 10 and an additional 200 lbs N/acre at year 14 to thinned and unthinned plots; however, no growth response was detected by year 20 (Mainwaring et al. 2004). Similarly, no growth response to fertilization was detected after two different levels of nitrogen were added in slow-release NPK mixes to stands exhibiting different levels of SNC intensity (Rose and Rosner 2004).

Other fertilizer trials for heavily infected stands have been established using the Diagnosis and Recommendation Integrated System (DRIS) approach to develop nutrient prescriptions based on nutrient ratios and balances implied from foliar analysis (Beaufils 1973). Weiskittel et al. (2004) found a positive growth response in 5-10-yr-old plantations identified to have an excess of N and treated with a blend of Ca, P, K, Mg, S, B, and Zn. However, this response was confounded with herbicide treatments implemented along with the fertilization treatment. In part of the same study, 11-15-yr-old stands showed no response to fertilization (Weiskittel et al. 2004), but older infected stands (35-40 yrs) have shown a positive response to similar nutrient additions (Mainwaring et al. 2005 data).

The goal of the current study was to provide an initial test of the efficacy of different operational fertilizer blends for enhancing tree growth, and to quantify any possible gains from addition of other nutrients to conventional nitrogen fertilization, particularly in SNC impacted stands. The specific objectives were 1) to determine the growth response of young Douglas-fir stands to balanced nutrient additions; 2) test the influence of initial SNC severity on these responses; and 3) test and quantify treatment effects on SNC severity.

Methods

Study sites

Study plots were distributed across a range of soil productivity, elevation, and aspect in the Oregon Coast Range and west slope of the Cascade Mountains (42.56° to 44.89° N and 122.54° to 123.47° W; Figure 1). Two age classes were included: 8-12-yr-old, unthinned Douglas-fir plantations and 20-30-yr-old, thinned Douglas-fir plantations (table 1).

Treatments included an untreated control plus three separate fertilizer applications: 1) nitrogen only (N), 2) nitrogen, phosphorus, and potassium (NPK), or 3) nitrogen, phosphorus, potassium plus micronutrients (NPKplus). In addition, the rate of K in NPK and NPKplus treatments varied by initial SNC severity, with high severity receiving 250 lbs/ac and low severity receiving 110 lbs/ac. Eleven of the 16 plantations were considered affected by SNC, i.e., average initial foliage retention was less than 3.0 years. Treatments were replicated 10 times in 13 of plantations, and 8 times in the other 3. The absolute and relative value of each nutrient in the blends was based on consultation with soil scientists experienced with regional soils and on Douglas-fir nutritional requirements, but fertilizer composition and rates were uniform across

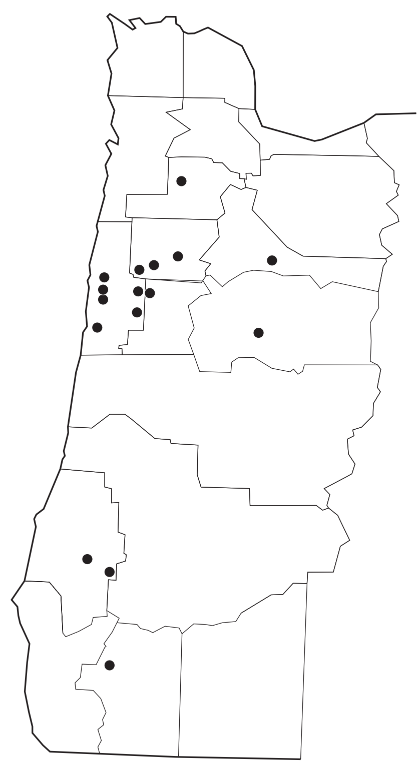

Figure 1. Plot locations for balanced fertilizer study.

Table 1. Description of study sites for the fertilization trials in western Oregon. Plots were established and treated during the winter of 1997-98.

Number	Site	Date planted	TPA	Site Index*	Number of miniplots	SNC level
1	Underhill	1967	197	130	40	H
2	Harlan	1972	627	140	40	H
3	Lightning tree	1981	326	136	40	H
4	Toledo	1991	488	125	40	H
5	1000 Line	1977	342	125	40	H
6	Bayview	1977	461	125	40	H
7	Coal Creek	1976	209	110	32	L
8	Marks Ridge	1967	205	130	40	L
9	Cold Springs	1965	206	100	32	L
10	Dutch Creek	1985	320	120	32	L
11	Swede Hill	1985	475	120	40	H
12	East Newton	1981	404	132	40	H
13	Fall Creek	1984	384	130	40	H
14	Rocky 20	1989	369	113	40	H
15	Fairview	1987	611	133	40	H
16	Kutch Creek	1983	413	110	40	L

*King (1966), feet at 50 yrs

sites with the exception of K.

Fertilizer treatments were randomly assigned to 0.025-ac miniplots in 8-12-yr-old stands, and 0.065-ac miniplots in 20-30-yr-old stands. Prescribed fertilizer rates were applied in two passes with a rotary spreader, with the second application perpendicular to the first. Fertilization took place between November 1, 1997 and February 28, 1998.

Two trees were sampled on each miniplot for growth measurements and SNC severity rating. These trees were not necessarily adjacent, but were similar in height and diameter. Measurements were made prior to the initial growing season following treatment, following the third growing season, and following the fifth growing season. Diameter, height, and crown length were measured on all sample trees to the nearest 0.1 in, 1 ft, and 1 ft, respectively, and local basal area was measured from miniplot center with a 20 ft^2/ac BAF prism. Swiss needle cast intensity was rated by several indices, including foliage color, crown density, foliage transparency, and the number of years of foliage retention. Foliage retention was measured by visually dividing a tree's crown length into thirds, estimating the number of years that foliage is retained to the nearest 0.5 years for each third, and averaging across crown thirds. Tree volumes were calculated using the Bruce and Demars (1974) equation for second growth Douglas-fir.

Foliar nutrient levels were analyzed for each of five randomly selected plots per treatment per site prior to fertilization. On each selected plot, current year needles were collected in the fall of 1997 from the third whorl from the top of both measure trees. All needles collected from the five plots sampled per treatment and were combined into a composite sample for that plantation. Foliage chemistry was analyzed by the Central analytical laboratory at Oregon State University.

Statistical analysis

Basal area and volume growth were analyzed under a randomized block design, but using a multiple regression model to accommodate several covariates. These covariates included initial tree size, crown size, stand density, and SNC severity. Fertilizer treatment effects were tested with four different models: 1) as a base model with block effects and; 2) the base model with interactions between treatment and initial foliar nitrogen; 3) the base model with interactions between treatment and initial

Table 2 Fertilizer application rates for balanced fertilizer trial, Active rate (lbs./acre)

Nutrient	Amount (lbs/ac)				
	Trt 1 NPK low K	Trt 2 NPK high K	Trt 3 NPKplus, low K	Trt 4 NPKplus, high K	Trt 5 N
N	200	200	200	200	200
P	60	60	60	60	-
K	110	250	110	250	-
Mg	-	-	50	50	-
S	-	-	80	80	-
B	-	-	2	2	-
Cu	-	-	10	10	-
Fe	-	-	5	5	-
Zn	-	-	15	15	-
Ca	-	-	50	50	-

SNC severity; and 4) the base model with interactions between treatment and both initial SNC severity and foliar nitrogen percent.

Results

Five-yr basal area growth

Simple model

The randomized block model with covariates explained approximately 73% of the variation in the logarithm of 5-yr basal area growth (MSE = 0.0564). After accounting for block effects, initial Douglas-fir basal area (BAi), local basal area (SBA), initial crown ratio (CRi), and initial foliage retention (FR), all three fertilizer treatments resulted in a significantly positive growth response (Table 3). Growth on the N, NPK and NPKplus treatments was 10.6, 6.9, and 14.0% higher, respectively, than on the control. The only significant difference between treatments was a 6.6% greater basal area response with NPKplus than with NPK.

Foliar nitrogen

Response to treatment depended on initial foliar N, as indicated by the significant interaction (Table 3). NPKplus gave the greatest positive response to treatment ([trt-control]/control) at a given level of initial foliar nitrogen ranging from –7 to 36% as foliar N decreased from 2.2 to 1.2% (Figure 2). The relative efficacy of the other treatments depended on initial foliar nitrogen, with N alone providing a greater response than NPK if initial foliar N >1.6%, but NPK providing a greater response if foliar N <1.6%. The average response to all three treatments became negative at high levels of initial foliar N: >1.8% for NPK, >1.9% for N, and >2.0% for NPKplus (Figure 2).

Foliage retention

Initial foliage retention was not significantly related to basal area growth on control plots; however, its interactions with fertilizer treatment were all significant at α=0.05 (Table 3). Main effects of fertilizer treatments were not significant in the presence of interaction terms, indicating that response to fertilization depends on initial foliage retention. Basal area

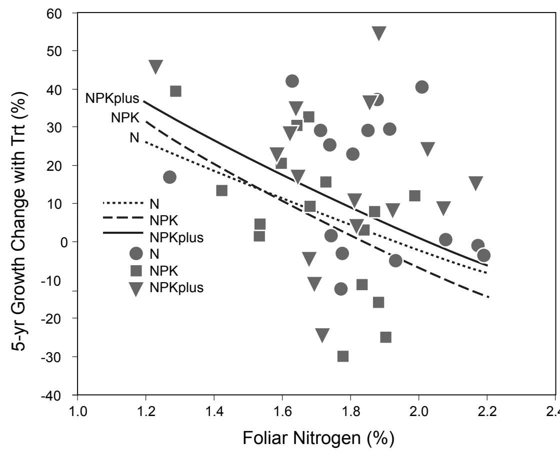

Figure 2. Five-yr basal area growth response to fertilizer treatment ([trt-control]/control) at different levels of initial foliar N% for all three fertilizer treatments. Solid shapes represent responses at different levels of foliar N.

Table 3 Parameter estimates for models describing basal area growth

	Simple model		Foliar N		Foliage retention		Full model (eqn [1])	
Parameter	Parameter estimate	(SE)	Parameter estimate	(SE)	Parameter estimate	(SE)	Parameter estimate	(SE)
INT	0.6866	(0.2640)	-0.2335	(0.4156)	0.7650	(0.2617)	0.1564	(0.4513)
N	0.1009	(0.0272)	0.6088	(0.2426)	-	-	0.4630	(0.2518)
NPK	0.0670	(0.0272)	0.7849	(0.2411)	-	-	0.6108	(0.2530)
NPKplus	0.1312	(0.0271)	0.7603	(0.2373)	-	-	0.5964	(0.2481)
fN	-	-	0.5320	(0.1767)	-	-	0.4212	(0.1838)
N*fN	-	-	-0.3166	(0.1377)	-	-	-0.3232	(0.1361)
NPK*fN	-	-	-0.4298	(0.1384)	-	-	-0.4405	(0.1398)
NPKplus*fN	-	-	-0.3769	(0.1367)	-	-	-0.3919	(0.1382)
ln(FR)	0.2495	(0.1059)	0.2308	(0.1056)	0.1540	(0.1070)	0.0586	(0.1303)
NFR	-	-	-	-	0.1188	(0.0289)	0.1918	(0.1151)
NPKFR	-	-	-	-	0.0846	(0.0289)	0.2285	(0.1133)
NPKplusFR	-	-	-	-	0.1502	(0.0288)	0.2198	(0.1119)
ln(BAi)	0.7137	(0.0286)	0.7055	(0.0285)	0.7127	(0.0285)	0.7063	(0.0285)
ln(SBA)	-0.2539	(0.0405)	-0.2559	(0.0402)	-0.2534	(0.0403)	-0.2579	(0.0402)
ln(CRi)	0.8377	(0.1164)	0.8331	(0.1158)	0.8338	(0.1161)	0.8340	(0.1158)
BLOCK								

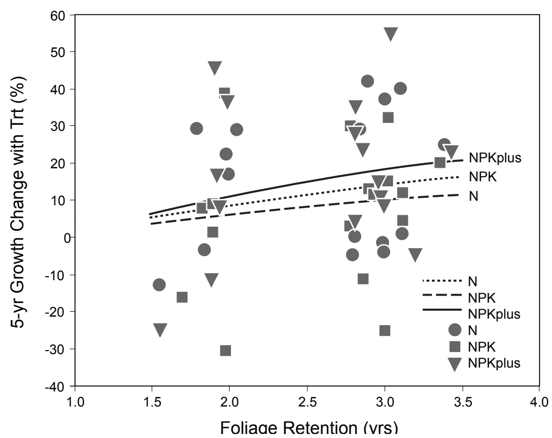

Figure 3. Five-yr basal area growth response to fertilizer treatment ([trt-control]/control) at different levels of foliage retention for all three fertilizer treatments. Solid shapes represent responses at different levels of foliage retention.

growth was positively correlated with foliage retention (Table 3). NPKplus produced the greatest positive responses, followed by N and then NPK treatment. Differences between the treatments increased with greater initial foliage retention: At a low foliage retention (1.5 yrs), responses among treatments differed by about 2%, but increased to about 5% at high foliage retentions (3.5 yrs) (Figure 3).

Full model

The full model contained both foliar nitrogen and foliage retention, as well as their interactions with fertilizer treatments.

[1] $\ln(BAG5) = BLOCK + a_0 + a_1\ln(BAi) + a_2(SBA) + a_3(CRi) + a_4(N) + a_5(NPK) + a_6(NPKplus) + a_7(fN) + a_8(N \bullet fN) + a_9(NPK \bullet fN) + a_{10}(NPKplus \bullet fN) + a_{11}\ln(FR) + a_{12}(N \bullet FR) + a_{13}(NPK \bullet FR) + a_{14}(NPKplus \bullet FR)$

where BAG5 = 5-year basal area growth of miniplot trees (ft^2)
BLOCK = Random block effects
BAi = Initial basal area of two miniplot measure trees (ft^2)
SBA = Basal area as measured by 20 BAF prism
CRi = average crown ratio of miniplot measure trees (expressed as decimal)
N = 1 if plot was treated with N, otherwise 0
NPK = 1 if plot was treated with NPK, otherwise 0
NPKplus = 1 if plot was treated with NPKplus, otherwise 0
fN = initial foliar nitrogen % (trt level)
FR = initial Foliage retention (yrs)

Response to fertilizer treatment is positively correlated with initial foliage retention and negatively correlated with initial foliar nitrogen % (table 3), consistent with the models containing effects of only one or the other. Main effects of fertilizer were generally significantly, although the main effect is marginal (p=0.066) for N alone. After including interactions, growth responses to fertilization were greater at low foliar N and at high foliage retention (Figure 4a-c): Response to all three treatments was negative in severely affected stands (foliage retention~1.5 yrs) and where foliar nitrogen levels exceeded 1.6-1.7%. Responses to all three treatments were in excess of 25% in stands with low SNC severity (~3.5 yrs foliage retention) and with foliar nitrogen levels <1.5%. At foliar nitrogen levels of 2%, responses in healthy stands ranged from 2% for NPK to 9% for NPKplus.

Five-year volume growth

Simple model

The randomized block model explained approximately 93% of the variation in the logarithm of 5-yr volume growth (MSE = 0.0349). After accounting for block effects, initial Douglas-fir basal area (BAi), local basal area (SBA), initial crown ratio (CRi), and initial foliage retention (FR), all three fertilizer treatments resulted in a significantly positive growth response (Table 4). Growth on the N, NPK and NPKplus treatments was 7.9, 6.4, and 10.5% higher, respectively, than on the control. The only marginally significant difference between treatments was the 3.8% greater volume growth response from NPKplus vs. NPK.

Foliar nitrogen

Volume growth increased with increasing initial foliar nitrogen (fN), but fertilizer treatments dampened the effect of initial fN. The increase in growth with fertilization depended on levels of initial foliage N (Figure 5). The response was greatest for NPKplus, followed by N when foliar N levels exceeded 1.7%. The average response to all three treatments became negative at high levels of initial foliar N%: >1.87% for NPK, > 1.93% for N, and >2.08 for NPKplus (Figure 5).

Foliage retention

Volume growth was not related to initial foliage retention on the control plots, but fertilizer responses increased significantly with increasing initial foliage retention (Table 4). Although all interaction terms were significant, only the NPK treatment had a significant main effect in addition to the interaction. The interac-

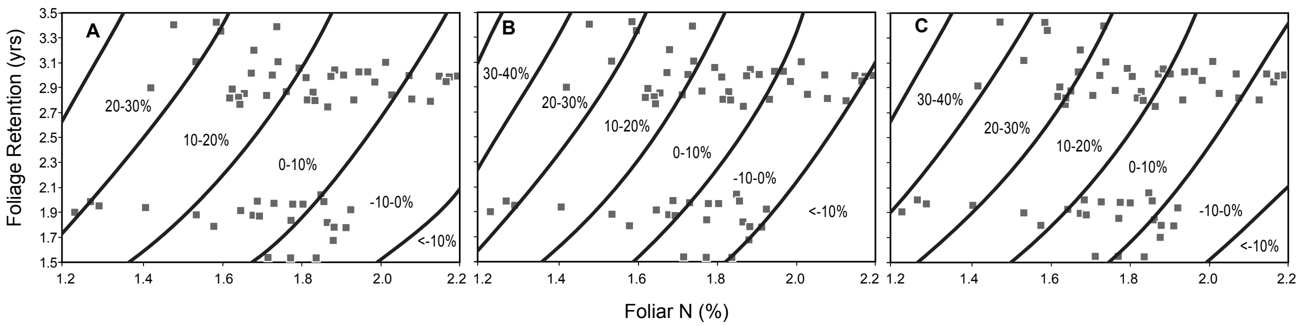

Figure 4. Five-yr basal area growth response to N fertilization ([trt-control]/control) at different levels of initial foliar N% and initial foliage retention. Solid squares represent treatment-level foliar N% and foliage retention averages.

Table 4 Parameter estimates for models describing volume growth

	Simple model		Foliar N		Foliage retention		Full model (eqn [2])	
Parameter	Parameter estimate	(SE)	Parameter estimate	(SE)	Parameter estimate	(SE)	Parameter estimate	(SE)
INT	1.5689	(0.2078)	0.8936	(0.3277)	1.832	(0.2331)	1.2731	(0.3549)
N	0.0757	(0.0214)	0.4677	(0.1913)	-0.1118	(0.0781)	0.3275	(0.1980)
NPK	0.0619	(0.0214)	0.5852	(0.1901)	-0.1551	(0.0768)	0.4132	(0.1989)
NPKplus	0.0996	(0.0213)	0.4839	(0.1871)	-0.1192	(0.0773)	0.3224	(0.1951)
fN	-	-	0.3882	(0.1394)	-	-	0.2810	(0.1446)
N*fN	-	-	-0.2426	(0.1086)	-	-	-0.2452	(0.1096)
NPK*fN	-	-	-0.3133	(0.1092)	-	-	-0.3265	(0.1100)
NPKplus*fN	-	-	-0.2328	(0.1078)	-	-	-0.2489	(0.1087)
ln(FR)	0.1624	(0.0834)	0.1465	(0.0833)	-0.0341	(0.0456)	-0.0222	(0.1025)
N*ln(FR)	-	-	-	-	0.2075	(0.0834)	0.1769	(0.0905)
NPK*ln(FR)	-	-	-	-	0.2400	(0.0820)	0.2308	(0.0891)
NPKplus*ln(FR)	-	-	-	-	0.2423	(0.0825)	0.2189	(0.0880)
ln(BAi)	0.8939	(0.0225)	0.8878	(0.0224)	0.8944	(0.0223)	0.8886	(0.0224)
ln(SBA)	-0.1391	(0.0319)	-0.1399	(0.0317)	-0.1422	(0.0317)	-0.1409	(0.0316)
ln(CRi)	0.4750	(0.0917)	0.4704	(0.0913)	0.4776	(0.0914)	0.4709	(0.0911)
BLOCK								

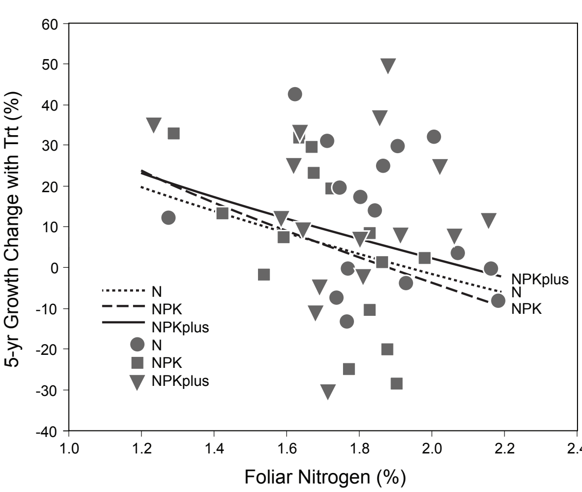

Figure 5 Five-yr volume growth response to fertilizer treatment ([trt-control]/control) at different levels of initial foliar N% for all three fertilizer treatments. Solid shapes represent responses at different levels of foliar N.

tion between foliage retention and the N and NPKplus treatments remained significant without the N and NPK-plus terms in the model. The growth responses to fertilization increased with initial foliage retention (Figure 6). NPKplus provided the greatest volume growth response with an average increase of 16% in healthy stands. The NPK treatment had the lowest level of response, giving an 11% increase over controls. At the lowest foliage retention, responses to all three treatments averaged only about 4%.

Full model

The response to fertilizer treatments increased with initial foliage retention and decreased with initial foliar nitrogen (Table 4). Main effects for N and NPKplus were significant only at the α =0.10 level. After including interactions, volume growth responses to fertilization were greater at low foliar N and at high foliage retention (Figures 7a-c).

In healthy stands, response to NPK was greater than response to N at all but the highest foliar N% (<1.9%); At lower levels of foliage retention response to N became greater. Regardless of treatment, the model implies that healthy stands with the highest levels of initial foliar N do not respond. In heavily infected SNC stands with foliar nitrogen levels

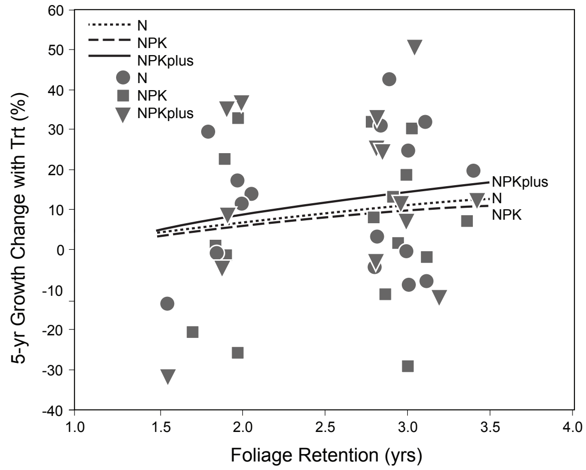

Figure 6. Five-yr volume growth response to fertilizer treatment ([trt-control]/control) at different levels of foliar retention for all three fertilizer treatments. Solid shapes represent response at different levels of foliage retention.

greater than 1.5-1.7%, the average response to all three treatments was negative.

Change in foliage retention

Five years after treatment, none of the three fertilizer treatments had significantly changed foliage retention compared to control plots. In general, foliage retention decreased on all plots, particularly on plots with initial foliage retentions above 2.5 years (Figure 8). The significant decline in foliage retention on some of the plots with high levels of initial foliage retention testify to the intensification of the disease and the expansion of the epidemic area in the years after 1998 (Kanaskie et al. 2004). However, high pre-treatment foliage retention at uninfected sites in the Cascade Mountains and southern Oregon also decreased. The change suggests that annual fluctuations in weather influence foliage retention on the regional scale.

Discussion

Numerous studies have indicated that response to fertilization declines with increasing site index. In one study of 11-19 year old plantations (SMC Type I) across a range in stand density, response to 200 lbs/acre of nitrogen fertilization four years after application depended on site index (Turnblom and Harrison 1999). Where site index was low (SI <= 105), fertilized plots grew 4 sq.ft/ac/yr more basal area than unfertilized plots (p=0.0001). At medium sites (105<=SI<=125), fertilized plots averaged 0.9 sq.ft/ac/yr greater basal area growth than unfertilized plots, though the differences were only marginally significant (p=0.0842). On high sites (SI > 125) fertilized plots showed no response to fertilization (p=0.83). Results from this study generally followed the same pattern, (when installations were divided into responders and non-responders by testing for treatment effects within each installation (Figure 9a)). Five of the seven responding plots have the lowest site indices in the dataset (≤ 120 ft at 50 yrs). The responding plot with the highest site index (133 ft) showed a positive response to the NPK and NPKplus treatments, but not to nitrogen alone. By contrast, of the nine non-responding plots, only one had a site index below 125 ft.

Studies looking at the relation between intensive management practices and site productivity have shown that factors such as genetically improved planting stock and vegetation management increase apparent site indices of plantations relative to those expected of natural stands on the same site (Flewelling et al. 2001). Given the lack of SMC plots showing significant growth response to nitrogen fertilization above site index 125, and given the frequency with which height growth trajectories exceed expectations based on natural stands, a logical conclusion is that nitrogen fertilization may be ineffective on these sites, at least, until later in stand development when less nitrogen is available.

Stands most likely to respond to fertilization are those where a shortage of the added nutrients are limiting growth, where fertilization

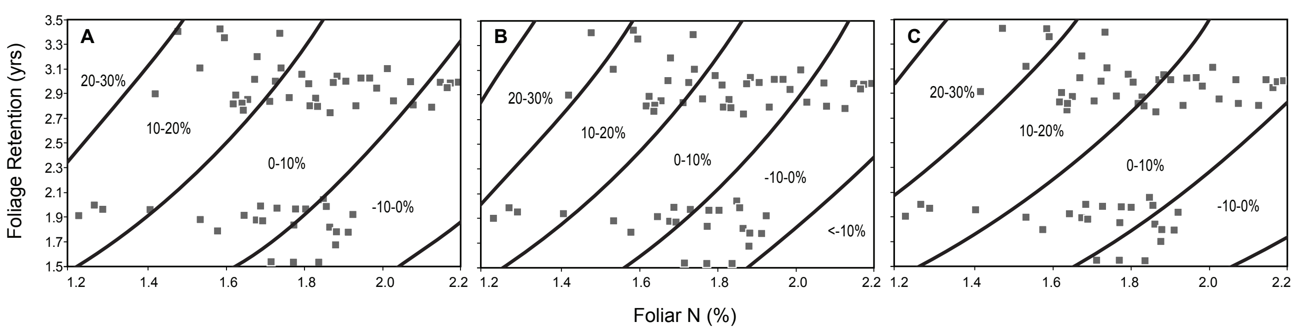

Figure 7. Five-yr volume growth response to N fertilizer treatment ([trt-control]/control) at different levels of initial foliar N% and initial foliage retention. Solid squares represent treatment-level foliar N% and foliage retention averages.

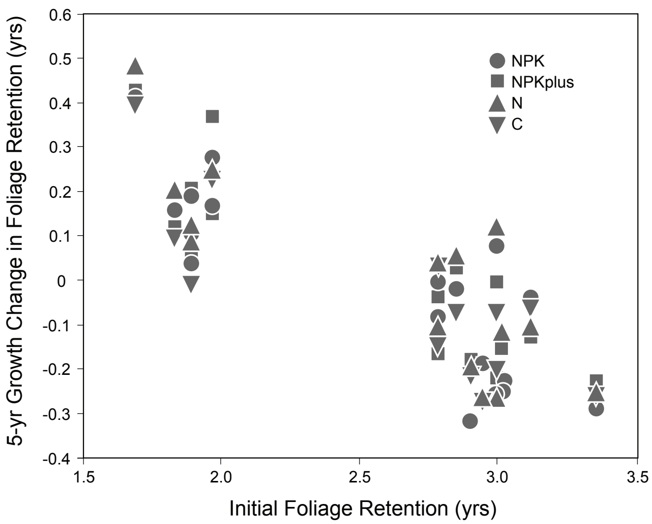

Figure 8. Five-year change in foliage retention by treatment type, ordered by initial control plot foliage retention.

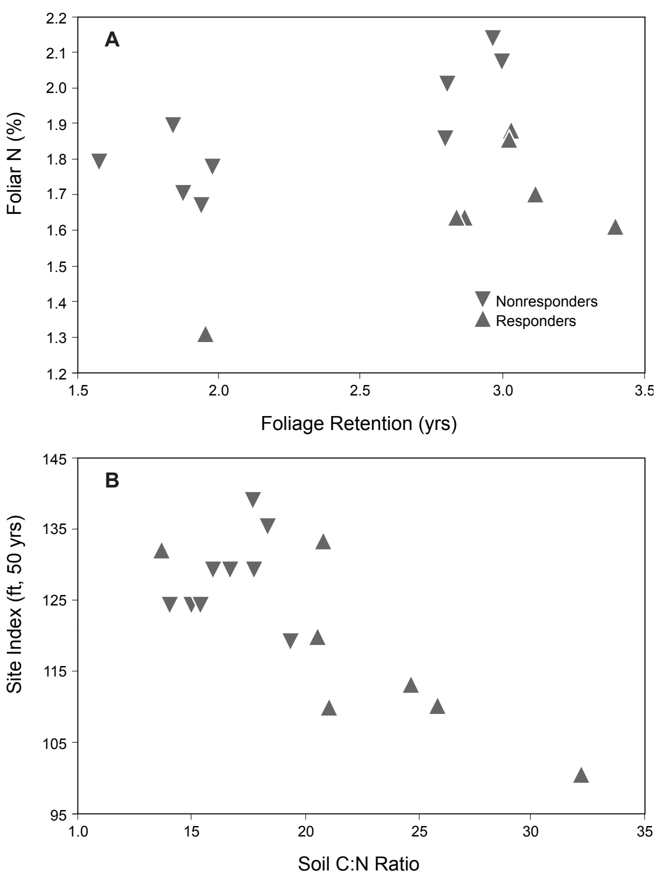

Figure 9a Distribution of responding and nonresponding installations by (a) initial foliage retention and foliar N% and (b) site index and soil C:N.

induces no other nutrient limitations, and where other inputs (light and water) are sufficient. Researchers in one study concluded that the probability of growth response to urea fertilization was low where foliar N exceeded 1.5% (Hopmans and Chappell 1994). Of the nine non-responding plots in this trial, the lowest foliar N was 1.68%, and the average was 1.89%. In contrast, the responding plots averaged 1.65% foliar N, and the plot with lowest foliar N (1.30%) had a marginally significant response to nitrogen fertilization, despite its severe SNC and high site index (132 ft). Prediction of responding sites as those with site index <125 would have correctly classified 80% of the stands in the balanced fertilizer study.

Another indicator of nitrogen availability on a site is the soil carbon:nitrogen (C:N) ratio. The growth response of Douglas-fir to nitrogen fertilization has been shown to increase linearly with soil and forest floor C:N (Peterson et al. 1984, Edmonds and Hsiang 1987). Edmonds and Hsiang suggested that, on average, stands with a C:N ratio below 27.5 would have no response to fertilization; however, only two of the 120 installations in their study had a C:N below 28. Of the 16 plots in the balanced fertilizer study, only one had a ratio exceeding this value, at 32.2. Nevertheless, C:N ratios on the non-responding installations were much lower than on responding installations (16.8 vs. 22.8; Figure 9b).

Previous studies have shown that nitrogen additions enhance Douglas-fir growth by densifying the crown (increasing leaf area density) and by increasing photosynthetic capacity and efficiency through increased foliar N% (Brix and Ebell 1969, Brix 1971, Brix 1981). Nitrogen additions to healthy stands have also been found to reduce foliage retention, perhaps because fertilization increased lateral branch growth while foliated branch length remained unchanged (Balster and Marshall 2000). Balster and Marshall hypothesized that reduced foliage retention resulted from increased shading of the older age classes. Self-shading would be unlikely in the already sparse crowns of heavily impacted SNC stands, suggesting a different mechanism for explaining the negative response implied for sites with high SNC and foliar N. A different possibility may be a consequence of the increases in foliar nitrogen levels resulting from fertilization: such increases have been found to provide a direct source of nitrogen for *P. gaeumannii* and have resulted in increases in fungal growth and fruiting rates (El Hajj et al. 2004). This increase in fungal mass and fruiting disrupts the photosynthetic capacity per needle (Manter et al. 2000), and speeds foliar loss.

While the effect of other nutrients on *P. gaeumannii* are unknown, fertilization of infected stands with nutrients in addition to, or in the absence of nitrogen has given mixed results. Adding other macro and micronutrients to nitrogen increased basal area and volume growth an average of 7.7 and 3.8% at all levels of foliar nitrogen and SNC infection. Previous studies incorporating nitrogen with other nutrients in the presence of SNC have not yielded significant growth responses. In one experiment, the equivalent of 3120 lbs/acre of slow release NPK blends (9-17-17 and 18-17-17) were applied in three 6-yr-old plantations. Though one of the sites was relatively free of SNC infection, fertilization with the equivalent of 280 and 561 lbs/acre of nitrogen over the space of three years elicited no response. The fact that all three sites were very productive (site indices of 124, 132, and 136) makes this result consistent with previous fertilizer research. Although highly productive sites should not be precluded from consideration for fertilization, their relative response tends to be lower (Miller et al. 1989), and determination of their growth-limiting factor is likely to be more difficult.

An SNC-infected stand may respond to nitrogen if it has low levels of foliar nitrogen. The likelihood of low foliar nitrogen among heavily infected stands is unknown, but the correlation between foliar N% and SNC infection was high (r=0.80) on a cross-section of stands used to monitor SNC (Maguire et al. 2000). Whether trees with high foliar N % are more susceptible to SNC, or whether severe SNC leads to high foliar N is unknown. High foliar nitrogen levels have been linked to enhanced *P. gaeumannii* development (El-Hajj et al. 2004), but another study looking at the host plant quality of trees chronically defoliated by pine sawfly found elevated foliar N levels compared to non-defoliated trees (McMillin and Wagner 1997).

Regardless of whether high foliar N is cause or effect of SNC infection, foliar analysis would be a very desirable prerequisite to any nitrogen fertilization in SNC-infected areas. Because research in the PNW previously demonstrated that N fertilization of Douglas-fir resulted in a significant growth response about 70% of the time (Miller et al. 1986), large-scale fertilization of Douglas-fir has been implemented assuming a 70% response rate. The rising cost of fertilizer and its delivery to target stands has intensified the need to improve the efficiency by predicting fertilizer response from site-level diagnostics. Given the relatively small growth response, stands with severe SNC should probably be excluded as candidates for fertilization at the rates used in this study.

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