Swiss Needle Cast Cooperative

Annual Report

2020

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USDA Forest Service

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Swiss Needle Cast Cooperative Staff

Dave Shaw – Director and Associate Professor of Forest Health

Gabriela Ritóková – Associate Director and Senior Faculty Research Assistant

SNCC Income Sources and Expenditures: 2020

Income	
Membership dues	*77,000*
Oregon State Legislature	*95,000*
Carry-over	*85,658*
Total 2020 Income	**$257,658**
Expenditures	
Salaries and wages	*124,002*
Travel	*9,112*
Operating expenses	*5,215*
Materials and Supplies	*4,185*
Indirect Costs (@17.5%)	*24,940*
Total 2020 Expenditures	**$167,454**
Balance	**$90,204**

SNCC Background and Organization

A major challenge to intensive management of Douglas fir in Oregon and Washington is 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. The SNCC is located in the Department of Forest Engineering, Resources and Management within the College of Forestry at Oregon State University. The Membership is comprised of private, state, and federal organizations. Private membership dues are set at a fixed rate. An annual report, project reports, and newsletters are distributed to members each year. Our objective is to carry out projects in cooperation with members on their land holdings.

SNCC Mission

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.

SNCC Objectives

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

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Note from the Director

Esteemed Members,

As you all know, 2020 was a crazy year, but as Gabi said, a perfect time to be in the woods. Gabi was able to complete the final-third of our scheduled 5-year remeasurement of our Research and Monitoring Plot Network this past Spring and Fall 2020! She was assisted by Doug Mainwaring and Andy Bluhm in the field, and Sky Lan in the lab. We measure diameters and heights in the fall, and sample foliage in the spring. Once the foliage is sampled this coming spring, the three-and-a-half-year cycle to complete the first set of plot measurements will be complete. This year, we collaborated with the Center for Intensive Plantation Silviculture (CIPS) to analyze the results. At our December meeting, it was reported that for a given level of foliage retention, the most infected stands are exhibiting up to a 35% volume growth loss, versus ~50% for the stands sampled in the 1998-2008 period. In addition, CIPS has produced a modified version of ORGANON that has new SNC diameter and height growth modifiers, and accounts for the influence of SNC on stem taper.

The bad news this year was that the Aerial Detection Survey (ADS) by ODF/USFS was canceled. Aerial Detection Survey is a key component of our monitoring program, so this is particularly disconcerting. This has also affected the state-wide ADS summer survey which did not occur last year. Our last ADS was in 2018, so we will cross our fingers that we can get one in for 2021. On the good news front, Gabi led a very nice paper for the Canadian Journal of Forest Research that was accepted this fall but will not come out until sometime this year. The paper is: *Ritóková, G., D.B. Mainwaring, D.C. Shaw, and Y.-H. Lan. 2021. Douglas-fir foliage retention dynamics across a gradient of Swiss needle cast in Oregon and Washington. Canadian Journal of Forest Research: Just in: Oct 12, 2020.* https://doi.org/10.1139/cjfr-2020-0318. We also have a SNC synthesis paper, "in-press", with the Journal of Forestry, which will come out this year. The paper is multi-authored and entitled, "*Persistence of the Swiss Needle Cast Outbreak in Oregon Coastal Douglas-fir, and New Insights from Research and Monitoring*".

Thank you, Members, for supporting the Swiss Needle Cast Cooperative,

David C. Shaw

David C. Shaw

Douglas-fir foliage retention dynamics across a gradient of Swiss needle cast in coastal Oregon and Washington

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Abstract

Swiss needle cast (SNC) is an important foliage disease of Douglas-fir (*Pseudotsuga menziesii*) caused by the native pathogen *Nothophaeocryptopus gaeumannii*, that has been present in epidemic proportions since the 1990s in coastal Douglas-fir forests. Under conducive environmental and stand conditions, the fungal fruiting bodies emerge on young needles, inhibiting gas exchange and causing premature needle casting and subsequent growth losses. Using a new regional plot network, which extends and approximately doubles the area of SNC-susceptible coastal forest sampled, we investigated the distribution of SNC disease indices across the region, and throughout individual tree crowns. Foliage retention varied from 1.15 to 3.9 years and disease severity (incidence x % occluded stomata) ranged from 0.05 to 52.11%. Foliage retention was positively correlated with distance from the coast and elevation. Foliage retention and disease severity were found to be negatively associated across the study area. Within crowns, disease severity was negatively associated with crown depth, and foliage retention was positively associated with crown depth, regardless of distance from coast. Across the entire study, foliage retention was found to decrease, and disease severity increase with latitude, all else being equal. Tree growth metrics are positively associated with increasing foliage retention, and normal growth occurs greater than ~3.2 years.

Key Words: Swiss Needle Cast, *Nothophaeocryptopus gaeumannii,* Foliage Retention, Douglas-fir.

Introduction

Swiss needle cast (SNC) is a species-specific foliar disease affecting Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and is caused by *Nothophaeocryptopus* (=*Phaeocryptopus*) *gaeumannii*. (T. Rohde) Videira, C. Nakash., U. Braun & Crous, (Mycosphaerellaceae), a recently reclassified ascomycete fungus (Videira et al. 2017). The Pacific coastal forests have seen SNC emerge as a significant threat to Douglas-fir plantation productivity since the 1990s (Hansen et al. 2000, Shaw et al. 2011, Ritóková et al. 2016). The pathogen causes growth and volume reduction of Douglas-fir due to reductions in gas exchange (Manter et al. 2000) and premature casting of needles (Hansen et al. 2000, Maguire et al. 2002, 2011), although disease-caused tree mortality is rare (Maguire et al. 2011).

Nothophaeocryptopus gaeumannii is a fungus that grows internally in the leaf. Disease occurs when spore-producing fungal structures plug the stomata. Based on observations of heavily colonized live needles, it has been estimated that needles are cast when approximately 25

– 50% of the stomata are plugged (Hansen et al. 2000, Manter et al. 2003). Disease severity is determined by measuring the percent of plugged stomata on 2-year-old needles, which reflects the potential for young needles to be cast. Estimates and modeled growth impacts from SNC have been based on foliage retention in years, i.e., the number of retained annual needle cohorts (Maguire et al. 2002, 2011). Quantifiable volume growth losses have been apparent when fewer than three years of foliage is retained, and 10-30 year-old Douglas-fir plantations in the NW Oregon Coast Range have been estimated to have an average annual cubic volume growth loss of ~23%, and average cubic volume growth losses can exceed 50% on the most severely infected sites (Maguire et al. 2011). Foliage retention has previously been shown to be correlated with disease severity in limited ranges within the zone of the SNC epidemic (Hansen et al. 2000, Manter et al. 2005).

Foliage retention in conifers varies naturally on the landscape, especially along site-productivity and elevation gradients, although tree age and stand dynamics are also influential (Schoettle 1990, Reich et al. 1995, Xiao 2003). In general, conifer foliage retention is lowest in the highest productivity sites, and increases with decreasing productivity, and increasing elevation and latitude (Reich et al. 1995, Balster and Marshall, 2000, Xiao 2003). The interaction of foliage disease with foliage retention complicates the natural patterns on the landscape by reducing foliage retention in certain geographic locations (Shaw et al. 2014). Weiskittel et al. (2006) found that on the tree level, *N. gaeumannii* reduced the amount of foliage mass in each age-class, increased the relative amount of foliage in younger age-classes, and increased the relative amount of foliage mass towards the base of the live crown.

Disease severity and symptoms of SNC (low foliage retention and leaf area, chlorotic foliage, and reduced tree growth) are most severe at lower elevations near the coast and lessen with increasing elevation and distance from the coast (Hansen et al. 2000, Rosso and Hansen 2003), with these two factors being partially co-linear in the Coast Range. Ritóková et al. (2016) also demonstrated that foliage retention increased with increasing elevation on the west slope of the Cascade Mountains in Oregon where SNC is present, but where disease symptoms are limited to moist low elevation stands.

Climate in the Oregon Coast Range is influenced by the longitudinal elevation profile and is a highly significant factor related to SNC severity. Winter temperature and leaf wetness during spore dispersal from May through August have been identified as the main epidemiological factors positively associated with the disease (Michaels and Chastagner 1984, Hansen et al. 2000, Manter et al. 2005). Consistent with epidemiological models, Zhao et al. (2011, 2012) found correlations between coastal Douglas-fir foliage retention and a temperature-based continentality index as well as a suite of other variables encompassing seasonality of both temperature and precipitation (Manter et al. 2005). Lee et al. (2017) used tree ring width chronologies to show that SNC can impact growth across the region and is not limited to the coastal fog zone. The study found that impacts were synchronous and linked to winter and summer temperatures, and summer precipitation, with the specific influential factors dependent on regional location.

Visible symptoms of SNC (chlorotic foliage and thin crowns) have been assessed by a Cooperative Aerial Detection Survey (ADS) in Oregon annually from 1996 – 2016, and again in 2018, by US Forest Service, Forest Health Protection and Oregon Department of Forestry. Washington Department of Natural Resources (WADNR) has performed ADS in 1998, 2000, 2012, 2015, 2016, and 2018, and British Columbia Ministry of Forests' inaugural flight took place in 2018.

Aerial surveys have generally found few visible SNC symptoms in southern coastal Oregon. The SNCC conducted limited sampling of Douglas-fir growing in coastal stands of southern Oregon in 2009 (Shaw and Woolley 2009), where it was found that foliage retentions were generally greater than were those in north coastal Oregon for a given distance from the coast. Though these measurements were ultimately used within a larger dataset for correlating climate variables with foliage retention, they were not subject to further analysis. Correlations between climate and foliage retention, extrapolated to unsampled areas along the southern Oregon coast, have predicted lower foliage retentions than the aerial survey results have coarsely implied (Coop and Stone 2007), making regionwide assessments of disease impact questionable, and greater sampling within these areas valuable.

A substantial body of published research has been produced since the onset of epidemic conditions across coastal Pacific forests in the 1990s, spearheaded and financed through industry and agency collaboration within Oregon State University's Swiss Needle Cast Cooperative (SNCC). This effort, encompassing the first 15 years of focused SNC research, was primarily based on conditions in NW coastal Oregon (>44.6°N), where epidemic conditions were first identified (Coop and Stone 2007; Hansen et al. 2000; Maguire et al. 2011; Manter et al. 2005; Rosso and Hansen 2003; Shaw et al. 2014). With further spread of the disease evident, subsequent efforts have been made to expand the geographic range of monitored sites. This has culminated in the establishment of a new research and monitoring plot network installed by the SNCC (http://sncc.forestry.oregonstate.edu/) extending from the northern California border to SW Washington, (560 km (338 miles)) and 56 km (35 miles) inland (Fig. 1), which complements the ADS survey (Fig. 2) and provides an opportunity to investigate how foliage retention and disease severity vary on both a small and large scale: within crowns and geographically throughout Douglas-fir plantations across a gradient of disease symptomatology.

Previous work by the SNCC using a dataset geographically limited to the NW Oregon Coast Range found that SNC reduced Douglas-fir cubic volume growth and foliage retention across the western slopes of the Coast Range. Because symptom severity is correlated with climate variables, and because climate change may be a persistent agent, periodic updating of sampling and analysis is considered of value, particularly with a geographically expanded dataset. Our objectives were to validate the following predictions: 1) Foliage retention increases, and disease severity decreases with elevation and distance from the coast; 2) Foliage retention decreases with increasing disease severity; 3) Disease severity decreases, and retention increases from the top of the crown to the bottom of the crown; and 4) Foliage retention decreases, and disease severity increases with increasing latitude.

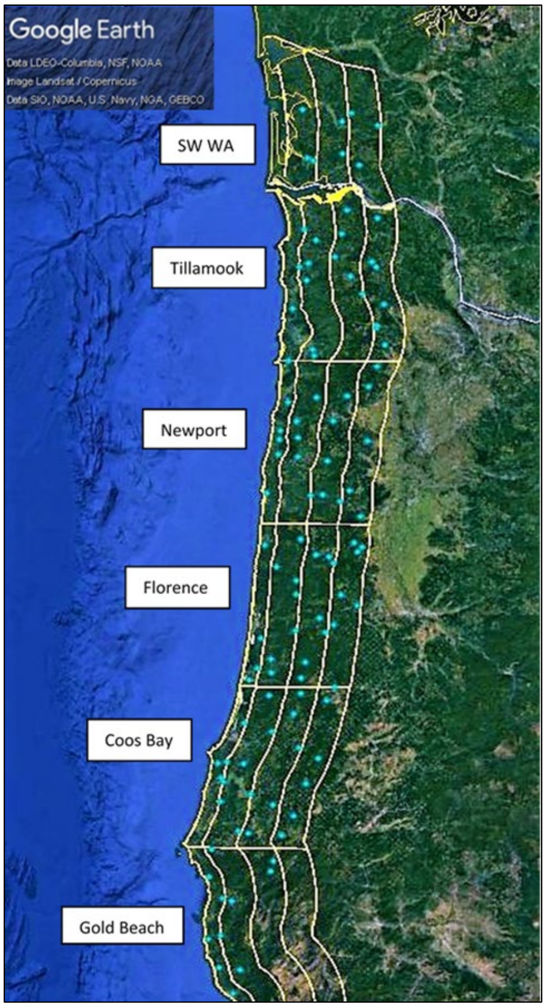

Figure 1. Distribution of 106 research plots established in 2013-2015 by the Swiss Needle Cast Cooperative (SNCC) in western Oregon and southwestern Washington (Ritóková et al. 2017). Latitudinal sampling zones from north to south are SW Washington (SW WA), Tillamook, Newport, Florence, Coos Bay, and Gold Beach.

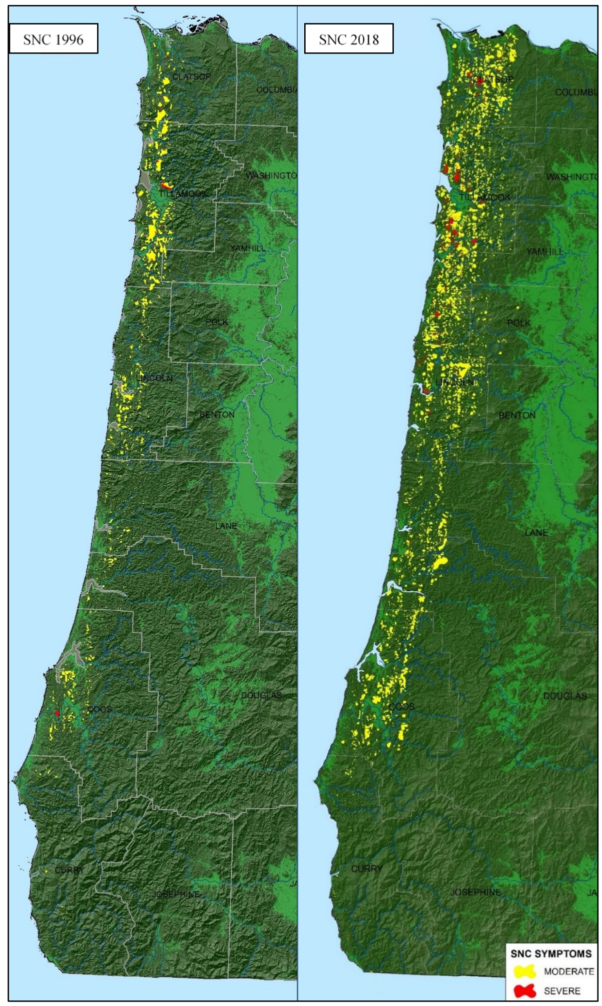

Figure 2. Areas of Douglas-fir forest with SNC symptoms in western Oregon detected by aerial survey in 1996 and 2018.

Methods

Study Area

Dominant forest types within the study region were Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) with a narrow zone of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) along the PNW coast (Franklin and Dyrness 1973). The geographical setting includes the Oregon Coast Range, and the Willapa Hills in SW Washington. Precipitation and temperature vary across the region due to elevation, latitude, and rain shadow on the eastern slope of the Coast Ranges. Annual precipitation ranged from 1200 - 4800 mm (47 – 190 inches), with the majority falling as rain from October through May. Mean annual temperature ranges from 13 - 18°C (55 - 64 °F). Elevation of the research plots ranged from 48 – 807 m (157 - 2,657 feet) above sea level.

Plot network and field methods

To capture a range of healthy to severely diseased stands, a sampling matrix was created for the Oregon and southwest Washington Coast Range extending from the California border to Aberdeen, Washington and 56 km (35 miles) inland from the Pacific Ocean. The region was divided into four longitudinal panels west-to-east, with an 8 km-wide strip closest to the Pacific Ocean where stands are severely affected by SNC, and three 16 km-wide strips making up the remainder. Each of the six latitudinal panels north-south was approximately 92 km (57 miles) long, resulting in 24 sample blocks (Fig. 1). The SNCC research and monitoring plot network includes 106 plots, of which 98 plots were located in coastal Oregon and 8 plots in southwestern Washington. An average of five study plots were located within each sample block. The four southernmost west-east blocks did not have a suitable selection of target Douglas-fir plantations and were therefore limited to eleven plots. Plots were established in the fall of 2013, 2014 and 2015 and sampled for disease severity and foliage retention in spring of the following year: 2014, 2015, 2016.

The plot installation protocol followed the Maguire et al. (2011) methodology to allow for integration with the growth impact sampling methodology of 1998-2008. Square plots were 0.08 ha (28.45 x 28.45 m) in area with a 10 m buffer around the perimeter of each plot. The target age of Douglas-fir plantations was 10- to 25-years-old, with older trees (20-25 yrs) acceptable in heavily infected areas where SNC-related height growth losses resulted in crowns that were sufficiently accessible for sampling. The target basal area composition was 80% Douglas-fir and preferred stem density was 800-1000 TPH. At the time of establishment, all plot trees larger than 5 cm at breast height were tagged and measured at a height of 137 cm. A subset of 40 trees was measured for total height and height to crown base and included the 10 largest and four smallest by diameter at breast height (dbh), with the remainder distributed across the diameter distribution. All plots were established in plantations that had not been pre-commercially thinned or fertilized in the five years prior to establishment.

Laboratory Methods

The SNC disease severity index was determined following the methods of Mulvey et al. (2015). For each crown position on selected trees, 50 needles from year-2 cohorts (branchlets) of each sample branch were removed and attached to an index card (Fig. 3). Each needle was visually inspected with a dissecting microscope to determine presence or absence of pseudothecia. Incidence represented the percent of 50 needles with pseudothecia present. The first 10 needles with pseudothecia were measured for length (mm) and used to determine pseudothecial density by counting 100 stomata from a starting point randomly located within three zones (tip, middle and base) on each needle and averaging to determine % pseudothecial density. The SNC disease severity index was calculated by multiplying the incidence and the pseudothecial density.

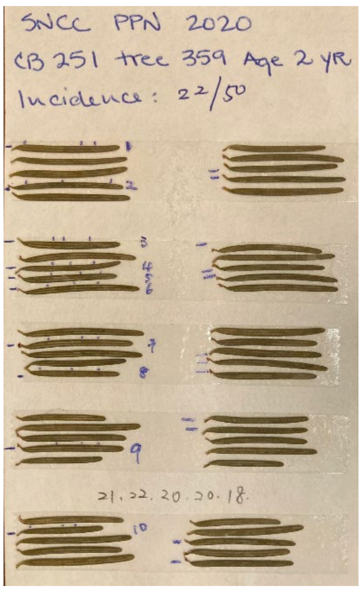

Figure 3. An index card with fifty Douglas-fir needles attached to evaluate disease incidence and pseudothecial density.

Statistical Analysis

Tests of significance for assessing differences in mid-crown foliage retention or disease severity index across the landscape were conducted using ANOVA or Analysis of Covariance (ANCOVA) within SAS PROC GLM. Distance from coast, elevation, January temperature, or June precipitation were used as either individual or combined covariates and latitudinal sampling zone was included as a categorical variable. Tests of significance for assessing differences in foliage retention or SNC disease severity index by crown position (upper, middle, or lower) and zone representing distance from the coast (0-8, 8-24, 24-40, or 40-56 km (0-5, 5-15, 15-25, or 25-35 miles)) were conducted using Analysis of Variance (ANOVA) within SAS PROC GLM in which crown position, zone, and their interaction were treated as separate categorical variables.

Results

The sample region encompassed a range of elevation (48 m – 807 m), foliage retention (1.15 years to 3.9 years), and disease severity (0.05 - 52.11) (Table 1). Foliage retention increased along a west-east gradient, with the lowest measured values along the northern coastline. Disease severity was more variable, exhibiting a decreasing gradient to the south. On the southernmost Oregon coast, plantations currently exhibit very little disease severity and higher foliage retention.

Site	Zone	Elev (av, m)	Foliage retention (yrs)	Disease Severity
SW_WA	8-24 km	166	1.93	25.96
	24-40 km	204	2.95	22.73
	40-56 km	313	3.05	22.63
Tillamook	0-8 km	256	1.78	22.32
	8-24 km	302	1.66	29.04
	24-40 km	457	2.68	13.29
	40-56 km	420	3.02	20.02
Newport	0-8 km	106	1.76	24.59
	8-24 km	334	2.29	18.47
	24-40 km	273	3.08	15.62
	40-56 km	263	3.16	15.73
Florence	0-8 km	123	1.61	20.4
	8-24 km	286	2.01	8.73
	24-40 km	263	2.79	12.73
	40-56 km	330	3.05	13.93
Coos Bay	0-8 km	124	2.12	18.15
	8-24 km	223	2.34	16.71
	24-40 km	285	2.61	11.61
	40-56 km	486	2.78	8.8
Gold Beach	0-8 km	402	2.56	9.84
	8-24 km	498	2.83	0.89
	24-40 km	753	3.3	1.57

Table 1. Swiss needle cast summary statistics by sampling block in the Oregon Coast Range and SW Washington.

Mid-crown foliage retention regressed against either distance from coast or elevation showed significant positive relationships (R^2=0.415 or 0.211 respectively; models 1 and 2, table 2), and accounting for both variables resulted in an R^2 of 0.489 (model 3, table 2). Additional use of a categorical variable to differentially account for the latitudinal sampling zones resulted in a R^2 of 0.574 (model 4, table 2). Distance from coast and elevation are usually thought of as coarse descriptors of topography, which in turn influence climate. When simple climate variables previously found to be associated with foliage retention (mean June precipitation and January temperature since 2000, http://prism.oregonstate.edu/explorer/bulk.php) were added to the full model, the latitudinal sampling zone categorical variable remained significant, but both distance from coast and elevation were rendered insignificant, and the correlation was slightly improved (R^2=0.582; model 5, table 2). Model-implied average foliage retention increased from north to south (Fig. 4).

Disease severity was found to have a significant negative relationship with elevation (R^2=0.199; model 6, table 2), elevation and January mean temperature (R^2=0.244; model 7, table 2), and a full model of elevation, January mean temperature and latitudinal sampling zones (R^2=0.422; model 8, table 2). No significant relationship with distance from coast or June precipitation was found. Model-implied average disease severity (full model) decreased from north to south (Fig. 5).

Disease severity was found to be negatively associated with mid-crown foliage retention (R2=0.179; model 9, table 2; Fig. 6), though this predictive relationship was improved by accounting for elevation (R2=0.26; model 10, table 2) or elevation and latitudinal sampling zone (R2=0.442; model 11, table 2).

Foliage retention varied by crown position ($p<0.0001$), zone ($p<0.0001$), and their interaction ($p=0.0314$; model 12, table 2), indicating that the relative vertical trends in foliage retention within the crown varied by distance from the coast (Fig. 7). In the two zones within 24 km of the coast, there was a distinct increase in foliage retention from the top to the bottom of the live tree crown, with each crown-third having a significantly different average foliage retention in each crown-third. In the two zones furthest from the coast, the upper crown third had a significantly lower foliage retention than the middle and lower crown-third, but the two lower crown-thirds did not differ significantly from one another.

Disease severity differed significantly by crown-third ($p<0.0001$; model 13, table 2). When analyzed separately by zone, disease severity of two-year old needles invariably increased from the bottom to the top of the crown, significantly so in the three zones furthest from the coast (Fig. 8). Disease severity tended to decrease with increasing distance from the coast for each crown-third but was greater in the lower and middle crown-third in the zone furthest from the coast.

Dependent variable	Model	Independent variable	F-Value	p-value
MID_CROWN_FOLRET	1	DFC	73.73	<0.0001
	2	ELEV	27.77	<0.0001
	3	DFC	55.93	<0.0001
		ELEV	14.84	0.0002
	4	DFC	71.45	<0.0001
		ELEV	4.48	0.0368
		SITE	3.92	0.0028
	5	DFC	2.47	0.1194
		ELEV	2.49	0.1175
		SITE	4.95	0.0004
		PPT_June	3.17	0.0782
		TEMP_Jan	7.22	0.0085
DIS_SEV, 2yr	6	ELEV	25.89	<0.0001
	7	ELEV	31.42	<0.0001
		TEMP_Jan	6.14	0.0148
	8	ELEV	7.01	0.0094
		TEMP_Jan	5.32	0.0232
		SITE	6.01	<0.0001
	9	FOLRET	22.68	<0.0001
	10	FOLRET	8.39	0.0046
		ELEV	11.21	0.0011
	11	FOLRET	9.15	0.0032
		ELEV	8.59	0.0042
		SITE	6.43	<0.0001
FOLRET by crown position	12	CR_POS	73.36	<0.0001
		Zone	26.07	<0.0001
		CR_POS x Zone	2.35	0.0314
DIS_SEV by crown position	13	CR_POS	26.87	<0.0001

Table 2. Results from ANOVA and ANCOVA tests for Swiss needle cast mid-crown foliage retention (MID_CROWN_FOLRET), disease severity for 2-year-old needles (DIS_SEV, 2yr), foliage retention by crown position (FOLRET by crown position) and disease severity by crown position (DIS_SEV by crown position). DFC = distance from coast, ELEV = elevation, SITE = plot site location, PPT_June = average precipitation for the month of June, TEMP_Jan = average temperature for the month of January, FOLRET = foliage retention, CR_POS = crown position (lower, middle, upper).

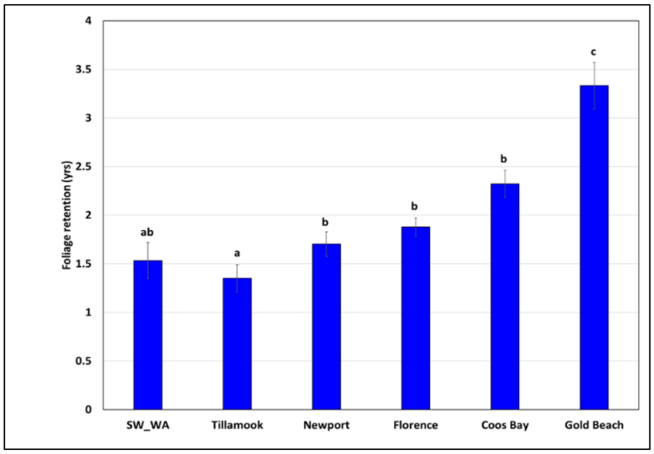

Figure 4. Implied foliage retention for the six coastal latitudinal zones based on an average June precipitation of 7 cm and an average January temperature of 5° C. Different letters represent the statistical difference between latitudinal sampling zones. Error bars denote standard error.

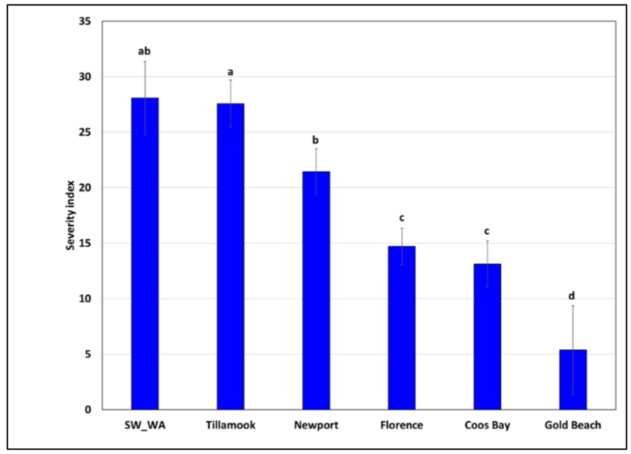

Figure 5. Implied disease severity ratings for the six coastal latitudinal zones based on an elevation of 100 m and an average January temperature of 5° degrees C. Different letters represent the statistical difference between latitudinal sampling zones. Error bars denote standard error.

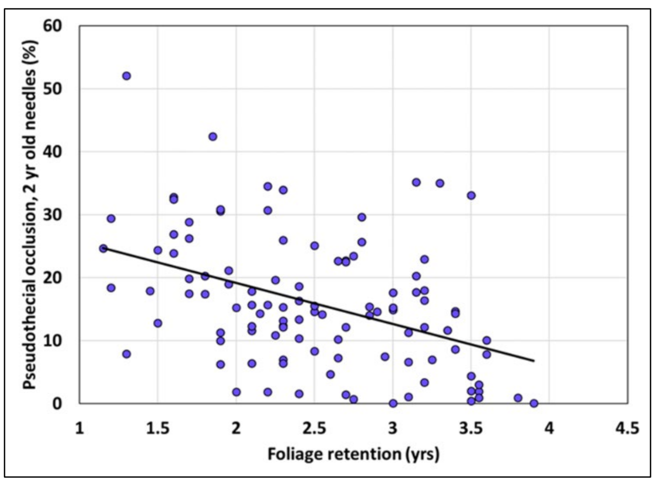

Figure 6. Distribution of occlusion percentage on 2-yr old needles versus the average plot-level mid-crown foliage retention (years).

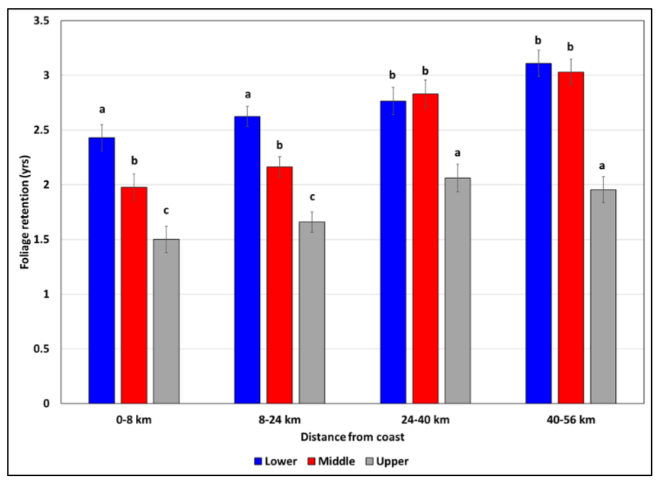

Figure 7. Differences in plot-level average foliage retention within the crown-thirds of trees within each longitudinal sampling zone. Different letters denote significantly different levels of foliage retention within each sampling zone.

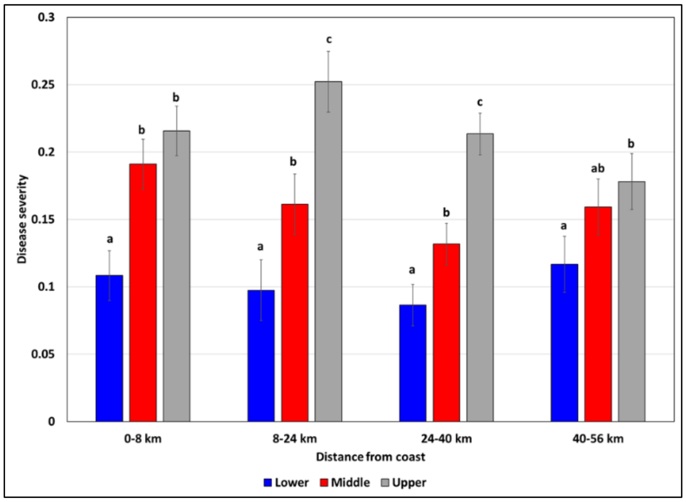

Figure 8. Differences in plot-level average disease severity within the crown-thirds of trees within each longitudinal sampling zone. Different letters denote significantly different levels of foliage retention within each sampling zone.

Discussion

Foliage retention was found to increase with elevation and distance from the coast, and disease severity decreased with elevation, in alignment with expectations. The positive correlation between foliage retention and distance from the coast and elevation was not surprising given previously published work from smaller scale studies (Hansen et al. 2000, Rosso and Hansen 2003) as well as correlative climate models (Zhao et al. 2011). Although decreased foliage retention in the coastal zones implies increased disease severity, a regional analysis of disease severity has not been previously published in the literature. While elevation was a significant predictor variable of disease severity, distance from the coast was not with or without the southernmost zone included in the analysis. This result is consistent with the high variation in pseudothecial occlusion observed across the region, and high rates of occlusion observed by the authors in stands as far east as the western Cascades, >100 km east of the Pacific Ocean. Unaccounted for in the examination of disease severity and occlusion are those needles that have been cast as a result of excessive occlusion, underscoring the interdependence of the disease severity and foliage retention, and the fact that a true qualitative assessment of SNC severity must also account for both. Likewise, it suggests that the estimation of volume growth loss using foliage retention as an index of SNC severity (Maguire et al. 2011) could be further refined by accounting for differences in occlusion (Fig. 6).

On the tree level, foliage retention was found to be positively associated with depth into crown, and disease severity was found to be negatively associated with depth into crown, consistent with the top-down pattern of infection originally identified in Hansen et al. (2000) and described quantitatively in Weiskittel (2003). Finally, models accounting for latitudinal sampling zone consistently found it to be a significant predictor of disease, with foliage retention increasing and disease severity decreasing at lower latitudes.

Foliage retention on the landscape

Landscape-level predictions of foliage retention can be useful for managers seeking to assess risk prior to Douglas-fir plantation establishment, likely current or future potential volume growth losses, or the effects of SNC on future harvest schedules. Recognizing the association between precipitation, temperature, SNC germination success, and pseudothecial development (Manter et al. 2005), numerous models have associated foliage retention with various climate variables (Coop and Stone 2007, Latta 2009, Zhao et al. 2011) with varying degrees of success.

While these models offer the potential of predictive flexibility that could be expected under changing climate scenarios, the amount of explained variability in foliage retention by Coop and Stone (2007) (R^2=0.56) and Latta (2009) (R^2=0.52) is not much greater than that explained by the coarse geographic variables such as distance from coast, elevation, and the categorical latitudinal sampling zones (R^2=0.489) described here. The three forementioned models did not have the benefit of copious foliage retention data collected from the southern half of the Oregon Coast Range, in some cases resulting in south coast foliage retention predictions that are inconsistent with the data collected as part of this study. Such inconsistencies also underscore the fact that climate is just one of the factors controlling successful fungal infection and development.

Addition of climate variables to the foliage retention model were found to improve the explanation of variation by replacing the coarse geographic variables with specific variables for which they are surrogates. Nonetheless, in each case, the categorical latitudinal variable for site remained significant with foliage retention predicted to increase and disease severity predicted to decrease from north to south after accounting for distance from coast, elevation, June precipitation or January temperature. A likely explanation for the mis-identified risk of low foliage retention along the southern Oregon coast (Zhao et al. 2011) is to be found in PRISM climate data (https://prism.oregonstate.edu/) from these plots, where average June precipitation in the plots making up the two zones closest to the coast in the Gold Beach region is 8.8 cm and mean January temperature is 8.0°C, while the values for the Newport and SW WA regions average 8.1 cm and 5.3°C. Correlations between these variables and foliage retention as presented in Zhao et al. (2011) would predict lower foliage retention, which is not supported by the measured data presented here.

The results from monitoring in the southernmost zones of the study area provide the greatest benefit from expansion of the original SNC monitoring network (Maguire et al. 2011) and raise questions about why SNC symptoms decrease despite a significant component of Douglas-fir and warmer winters. Conditions along the southern Oregon coast differ from the north in a number of ways, with the most apparent being contrasting soil types and relative fertility (Heilman et al. 1979). In previously studies, resource availability, manipulated in thinning or fertilization experiments have been found to influence conifer needle length (Brix and Ebell 1969, Raison et al. 1992, Tang et al. 1999). Among stands with healthy levels of foliage retention (≥3 yrs), mean needle length was significantly lower in the southern latitudinal sampling zones, with a whole crown average of 23.65 mm in the four northern zones, 21.68 mm in the Coos Bay zone, and 18.96 mm in the Gold Beach zone, suggesting limits to growth along the southern Oregon coast. Furthermore, when associations between mean needle length and foliage retention were assessed separately by latitudinal sampling zone, the associations were significantly positive in the four northernmost zones, consistent with the results found by Weiskittel (2003), but insignificant in the Coos Bay zone, and negative in the Gold Beach zone. In other words, in the north, diseased trees had shorter needles, suggesting that disease related-decreases in productivity could be limiting needle development. However, in the southernmost zone, diseased trees had longer needles, raising a question of whether some resource limitation somehow provided enhanced resiliency against disease. This possibility has been raised in a previous study (El-Hajj et al. 2004).

The incongruency between a lack of SNC symptoms and the presumed SNC-conducive climate along the southern Oregon coast found in climate models (Zhao et al. 2011) has been of interest to SNC researchers and is one of the reasons the SNCC research plot network was extended to include the entire Oregon coast. In the entire 0-8 km sampling strip closest to the ocean, the five plots of the Gold Beach zone exhibit milder SNC symptoms than those in other latitudes, significantly so for all but the Coos Bay zone. The five plots in the Gold Beach coastal zone had an average foliage retention of 2.56 years and an average disease severity of 9.84, versus 1.72 years and 22.6 for the three northernmost Oregon zones. Looking closer, of the five Gold Beach plots, two (GB_Infected) have characteristics similar to northern zones—an average foliage retention of 1.93 years and disease severity of 23.28. The three other plots in the same zone (GB_Uninfected) have an average foliage retention of 2.98 years and a disease severity of 0.88, providing an opportunity to draw contrasts between the two plot groups. Deployment of a combination of fungal spore traps, climate and leaf wetness sensors, and soil chemistry analysis may provide clues as to the reasons for the difference.

Factors influencing foliage retention

Most conifers depend on a 2 – 11-year complement of needles (USDA Field Guide, 2006) for healthy development and maximum productivity. Loss of older needles in conifers occurs annually and is not considered damaging. However, large proportions of foliage loss results in growth loss and sometimes mortality. Several biotic and abiotic factors cause foliar loss, and foliage retention of Douglas-fir in Coastal Oregon and SW Washington plantations is influenced by numerous environmental factors, including foliage disease. Particularly in coastal zones where SNC occurs, salt spray (Burkhardt 1995) or high winds (Ozolinčius and Stakėnas 1996) can affect foliage retention, as can biotic factors such as foliar pathogens and defoliating insects (Kurkela et al. 2009).

Nutrition has also been shown to influence foliar retention (Balster and Marshall 2000), and the soil nitrogen gradient in the coast range exhibits a generally negative association with the SNC symptom gradient (Perakis et al. 2013), making it difficult to partition how much the pattern of increasing foliage retention with distance from coast and increasing elevation demonstrated here is based on a fertility gradient and how much is based on spore concentration or the interaction of the two, as demonstrated in previous publications (Lan et al. 2019, El-Hajj et al. 2004). However, unlike SNC-influenced levels of foliage retention, fertility-influenced foliage retention does not result in sparser crowns and the estimable growth losses that have been found among Coast Range Douglas-fir plantations (Maguire et al. 2011).

Foliage retention in the crown

Relatively similar levels of average disease severity regardless of distance from the coast (Fig. 8) underscores the primacy of foliage retention as the index of SNC disease intensity. The greater increase in average foliage retention with distance from the coast (Fig. 7) relative to other crown depths, coupled with the greater foliage mass (Weiskittel et al. 2006) it represents validates the Maguire et al. (2002, 2011) application of mid-crown foliage retention as the best representative of disease levels upon which to estimate cubic volume growth in young Douglas-fir plantations. Shaw et al. (2014) also found lowest retention in the upper crown and highest retention in the lower crown across 76 permanent Growth Impact Plots (GIS) in the northern Oregon Coast Range. Our anecdotal observations suggest that needles in lower canopy position might be affected by other foliar pathogens such as *Rhizoctonia* and *Phytophthora* (Buhl, et al. 2016), or needle mortality due to limited light, resulting in imprecise association between SNC severity and foliage retention in the lower canopy. Often the upper crown of younger trees did not have four-year-old lateral branches, not allowing for comparable estimates of foliage retention with the other crown-thirds.

The SNCC (Shaw et al. 2011) has prepared recommendations for managers interested in maintaining productive stands within the SNC infection zone. For timber managers, Douglas-fir has traditionally been the preferred species due to its high productivity and market value. Planting decisions made under the assumption that salable forest products in forty years resemble those of the present must be informed by growth rates and market values of currently available species. In areas subject to high SNC pressure, there has been a notable shift towards increasing the amount of western hemlock on the landscape due to fears that the current SNC epidemic will not wane, and that regardless of its lower value in the current market, it will at least ensure a stand with a merchantable product in a financially realistic time frame. Geneticists have advised the use of SNC-tolerant Douglas-fir families under moderate disease levels (Johnson 2002, Jayawickrama et al. 2012).

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Volume growth losses within Swiss Needle Cast Infected Douglas-fir plantations, 2013-2020

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Abstract

Stand-level cubic volume growth losses were estimated for the first remeasurement of the Swiss needle cast Cooperative's Research Plot Network (RPN). Stands with only 1.0 years of foliage retention were estimated to have a 30-35% cubic volume growth loss, depending on the estimation procedure. This range is significantly lower than the 50%+ growth loss estimates made during the 1998-2008 period. This is believed to be due to a different sampling population, with many of the poorest performing stands having been harvested and replanted to non-susceptible species.

Introduction

Swiss needle cast (SNC) is a disease caused by the endemic foliar fungus Nothophaeocryptopus gaeumannii. The disease leads to significant increment losses in Douglas-fir through two primary mechanisms. The fungus grows into needles, eventually occluding stomates with fruiting bodies and decreasing stomatal conductance and rates of CO_2 assimilation (Hansen et al. 2000; Manter et al. 2000). Where infections are sufficiently severe, this ultimately causes premature loss of older foliage, reducing mean foliage retention to as little as one year and volume increment by as much as 50% (Maguire et al. 2011).

Previous analyses addressing the effects of SNC on volume growth during the 1998-2008 sampling periods estimated cubic volume growth losses in the most infected stands (foliage retention 1.0 yrs) of ~50%, ranging from 37 to 58% depending on growth period. Since the original effort, symptomatic acreage identified by aerial survey has increased (Navarro and Norlander 2018) despite the harvest or liquidation of many badly infected stands. Comparison of the former results with those from the now completed first remeasurement (2014-2020 growing seasons) of the SNCC's

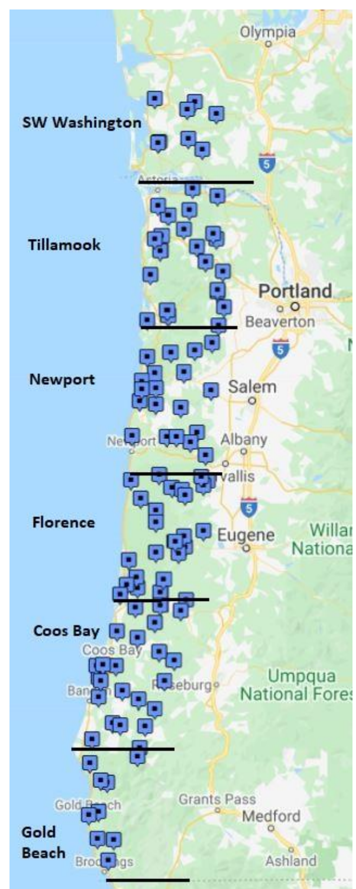

Figure 1. Map of SNCC RPN sites.

RPN will make it possible to assess whether there have been any commensurate effects of an expanding epidemic on stand volume growth losses.

The specific objective of this study was to develop a stand-level SNC-influenced volume growth equation for young Douglas-fir plantations in the Coast Range and use it to assess Douglas-fir cubic volume growth loss.

Methods

Study Sites

Data for this analysis were contributed by the Swiss Needle Cast Cooperative at OSU from their new Research Plot Network (RPN, Ritóková et al. 2015). One hundred and six plots were installed over three years between 2013 and 2015 on predominately Douglas-fir sites to investigate the influence of SNC on increment losses. Plots were established across a range in topographic positions and SNC severity. Latitudes ranged from the Oregon-California border (42.06°N) to SW Washington (46.65°N), and from the Ocean (124.41°W) to 35 miles inland (123.27°W), and elevation ranged from 150 to 2500 ft above sea level (fig. 1).

The first five-year remeasurement of the RPN was recently completed. The plots were distributed amongst a 6x4 cell sampling matrix (6 evenly distributed north-south sites and 4 east-west zones) to ensure an even geographic distribution. Site indices (Bruce 1981) were estimated from height-age pairs and ranged from 89-172 ft (50 yrs) and foliage retentions ranged from 1.15 to 3.90 years (Table 1).

Plot and Tree Measurements

All trees with diameter at breast height (DBH) ≥2 inches were tagged on 0.2 ac permanent plots. At plot establishment and during the remeasurement, DBH was recorded for all trees, and total height (HT) and height to lowest live branch (HLB) were measured on a subsample of Douglas-fir trees across the diameter range. In the spring prior to the first growing season of growth, five to ten dominant or codominant trees were scored in April or May for SNC severity. These trees were climbed, and foliage retention was estimated on the largest four-year old lateral branch of the southernmost primary branch from the whorl located closest to the center of the live crown. Plot-level retention was the average from each of the sampled trees.

SITE	ZONE	FOLRET (yrs)	SI (ft, 50 yrs)	SI_{adj} (ft, 50 yrs)	BH_Age (yrs)	TPA_DF	%BA_DF
SW Washington	5-15 mi.	1.9	126.4	138.8	13.7	398	75.3
	15-25 mi.	3.0	129.9	132.6	12.5	395	93.5
	25-35 mil	3.1	134.7	136.8	16.3	338	94.7
Tillamook	0-5 mi.	1.8	126.5	140.6	17.3	303	91.0
	5-15 mi.	1.7	124.8	140.3	12.8	401	99.6
	15-25 mi.	2.7	136.3	142.9	21.2	307	91.0
	25-35 mi.	3.2	130.8	133.0	15.8	322	95.7
Newport	0-5 mi.	1.8	127.4	142.1	17.6	307	81.0
	5-15 mi.	2.3	124.5	132.9	15.5	400	97.3
	15-25 mi.	3.0	145.0	147.5	17.5	299	98.5
	25-35 mi.	3.2	137.0	139.2	12.8	348	94.2
Florence	0-5 mi.	1.6	126.3	142.3	17.0	315	88.5
	5-15 mi.	2.0	142.9	155.7	14.3	448	99.1
	15-25 mi.	2.8	144.8	150.3	17.6	301	94.0
	25-35 mi.	3.1	146.8	150.3	16.4	434	98.6
Coos Bay	0-5 mi.	2.1	121.5	130.8	15.0	388	87.6
	5-15 mi.	2.3	146.5	155.0	19.0	272	98.5
	15-25 mi.	2.6	154.4	160.9	13.6	394	99.4
	25-35 mi.	2.8	143.8	149.1	17.8	352	96.8
Gold Beach	0-5 mi.	2.6	127.3	134.0	20.2	333	92.4
	5-15 mi.	2.5	130.7	137.6	14.3	657	96.7
	15-25 mi.	3.3	129.5	130.6	18.5	273	99.5

Table 1: Site and zone level statistics based on six north-south sites and 4 east-west zones shown in figure 1.

Site index

Tree growth is affected by site factors such as topography, climate, soil fertility, water holding capacity (Monserud et al. 1990, Weiskittel et al. 2011), and the current means of representing their combined effect in typical regional growth models like ORGANON is site index (Hann et al. 2006). Site index is also positively related to growth on the stand-level, though the recognized negative effect of SNC on height increment makes it challenging to accurately estimate it from height-age pairs in an infected stand. Using the site index estimated from height-age pairs in SNC-infected stands without any adjustment would result in an underestimation of growth loss, because the dominant heights upon which SI estimation is based would be lower than that expected in the absence of SNC.

A simple means of estimating the SNC-free site index, here termed SI_{adj}, was accomplished under the assumption that the trees of this plot network had experienced the same level of foliage retention throughout their lifetimes, and that the relationship between growth loss and dominant height could be properly described with the ORGANON-height modifier estimated by Hann et al. (2014):

$$SI_{adj} = \frac{SI_{measured}}{HTMOD_{Hann(2014)}} = \frac{SI}{(1+exp(-1.80657-0.0855 \cdot FR^3)}$$

This relationship elevated estimates of SI on infected plots as shown in figure 2.

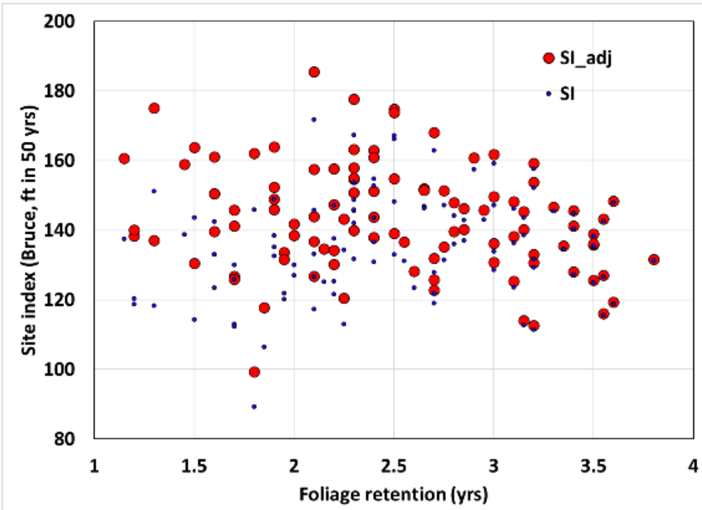

Figure 2. Relationship between SI and foliage retention, with and without adjustment

Data Analysis

All variation in initial needle retention was assumed totally controlled by SNC. A non-linear growth model was fitted to the data from 102 of the surviving RPN plots using SAS PROC NLIN, using initial foliage retention as the index of SNC severity:

$$[1] \qquad VPAI = a_0 \cdot (BA_{df}^{a1}) \cdot exp(BA_{ndf} \cdot a_2) \cdot SI_{adj}^{a3} \cdot (\mathbf{1} - exp(a_4 + a_5 \cdot FR^3))$$

where: VPAI=plot-level periodic annual cubic vol. increment for surviving Douglas-fir (m^3/ha/yr)

BAdf= plot-level Douglas-fir basal area (m^2/ha)

BAndf= plot-level non-Douglas-fir basal area (m^2/ha)

SIadj= Adjusted site index (m at breast height age 50 yrs)

FR= Plot level foliage retention (yrs)

Equation [1] was fit both with and without adjusted site index in the equation.

Results and Discussion

Parameter estimates and standard errors from the two fits of equation [1] are shown in table 2. Douglas-fir basal area, adjusted site index, and foliage retention were all positively correlated with Douglas-fir periodic annual cubic volume growth and non-Douglas-fir basal area was negatively correlated with it. Volume growth loss was implied to have a more curvilinear relationship with foliage retention than was the case in the 1998-2008 period, influenced by a different representation of foliage retention within the model describing volume growth. Nonetheless, plots of residuals vs. predicted values and vs. foliage retention show no systematic bias (figs. 3 and 4).

	With adjusted SI		Without SI	
Parameter	Estimate	Standard Error	Estimate	Standard Error
a_0	0.3992	0.2205	7.773	1.2937
a_1	0.3132	0.0454	0.3526	0.0502
a_2	-0.0297	0.00798	-0.0408	0.00911
a_3	0.8242	0.1458	NA	NA
a_4	-0.9217	0.1754	-0.987	0.2959
a_5	-0.1349	0.0466	-0.1848	0.0852

Table 2. Parameter estimates and standard errors from equation [1] with and without adjusted site index included.

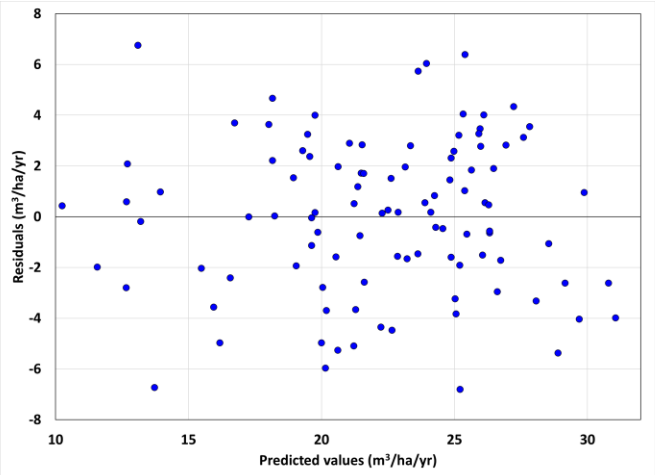

Figure 3. Residuals vs. predicted values based on equation [1], using adjusted site index.

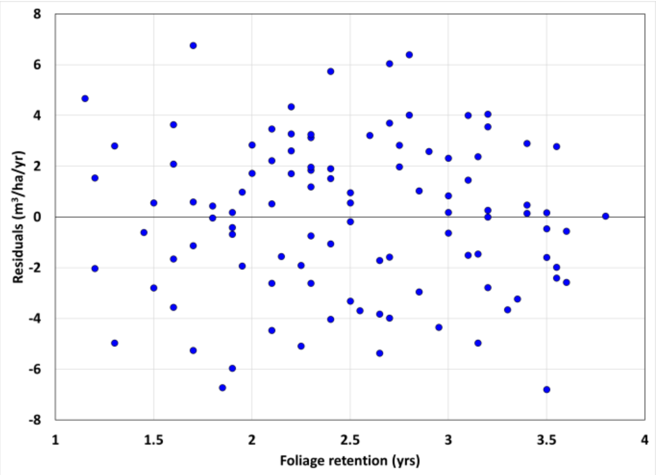

Figure 4. Residuals vs. foliage retention based on equation [1], using adjusted site index.

Cubic volume growth loss at a foliage retention of 1.0 yr was implied to be ~35% when using adjusted site index in equation [1] and ~31% when adjusted site index was not used (fig. 5).

Stand-level cubic volume growth losses estimated for the four separate growth periods between 1998 and 2008 varied from 37-58%, significantly greater than the 31-35% estimated here. Both datasets are believed to represent the population of Coast Range Douglas-fir plantations present during their periods of measurement, but in the 15 years prior to the establishment of the RPN, landowners of SNC-impacted stands recognized slow tree growth in their holdings, harvesting many merchantable stands and in some cases liquidating pre-merchantable stands and replanting to western hemlock or other non-susceptible species. Consequently, it is believed that the population of infected stands is different now than in the earlier period, and that the RPN better represents what currently exists.

Another explanation for the decrease may be the greater geographic distribution of the current dataset. While the original plot network (1998-2008) was limited to the NW Oregon Coast Range, the current dataset is distributed across the entire Oregon Coast Range, and as far south as the California border. Analysis of the geographic distribution of foliage retention and disease severity suggests that for a given level of foliage retention, stands of the southern Oregon coast generally have lower levels of infection and stomatal occlusion than occurs in stands further north (Shaw et al. 2021). This gives a greater relative weight to stands that may have lower occlusion rates in the current dataset, though differentiation of the northern and southern zones within equation [1] through use of an indicator variables did not yield significant results.

While the current analysis indicates that growth losses have decreased, if much of this is influenced by harvests of the most impacted stands and creation of a less impacted sampling population, it would also suggest that re-establishment of Douglas-fir plantations in disease-susceptible coastal zones could re-create the conditions that were associated with the greater growth loss estimates.

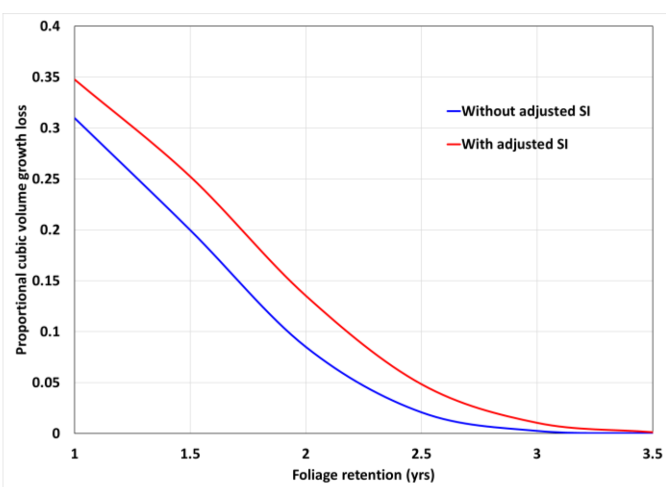

Figure 5. Implied volume growth losses from equation [1].

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Effects of Swiss needle cast on stem taper and its incorporation into ORGANON

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Abstract

A modifier to account for the negative effect of Swiss needle cast infection on upper stem diameter of rotation aged trees was constructed from stem analysis of 86 trees sampled 18 plots of the Swiss needle cast Cooperative's Growth Impact Study. These trees, aged 26-40 at the time of sampling in 2015, had experienced a range of SNC infection, with foliage retentions varying from 1.1 to 3.8 years when last assessed for foliage retention in 2008. Kozak's 1988 model form was used to predict the ratio of measured upper stem diameters on infected trees relative to predicted upper stem diameters under the assumption of no SNC. The modifier predicted up to a 10% decrease in upper stem diameter for the most infected trees at approximately 50% of total height. Applied to actual tree lists of rotation age, standing cubic and Scribner volume were estimated to be 5-10% lower in stands with low foliage retentions. The modifier accounting for the SNC effect on upper stem diameter has been incorporated into a version of the ORGANON 9.1 DLL, available to SNC Coop members.

Introduction

Swiss needle cast (SNC) is a disease caused by the endemic foliar fungus *Nothophaeocryptopus gaeumannii*. Sufficiently severe infections ultimately cause premature loss of foliage, with greater relative losses in the upper crown (Hansen et al. 2000). The increment impact of SNC can be estimated in numerous ways, but all depend on the relationship between some index of SNC severity and observed increment relative to that expected in the absence of SNC. Foliage retention, the number of annual cohorts of foliage retained, is currently the primary index of SNC severity (Hansen et al. 2000).

The distribution of diameter increment throughout the height of a tree is strongly dependent upon crown size and condition (Larsen 1963). The deleterious effects of Swiss needle cast (SNC) on total foliage mass and its alteration of foliage distribution throughout the tree crown (Weiskittel et al. 2006) spawned previous efforts to quantify the effect of SNC on stem taper (Weiskittel and Maguire 2004, Mainwaring et al. 2016), with results indicating that longer exposure to the SNC pattern of defoliation resulted in smaller upper stem diameters for a given dbh and height.

The goal of this report was to describe the construction of a modifier for predicting the effect of SNC on upper stem diameter. This modifier has been inserted into ORGANON source code to modify the Hann (2011) estimate of upper stem diameter within the two models.

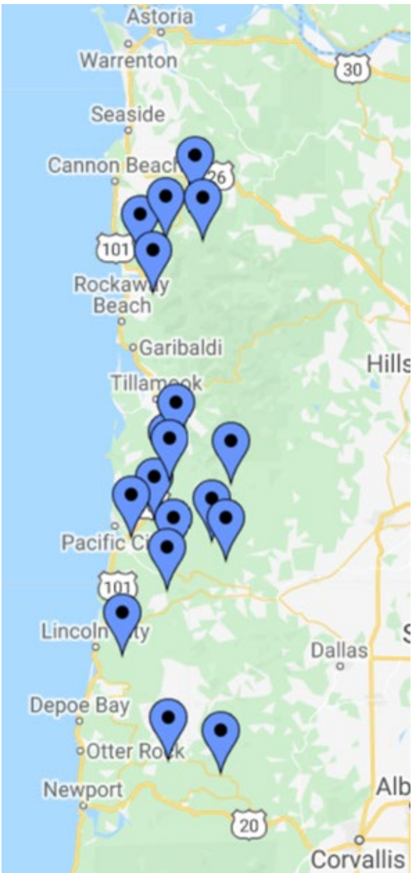

Figure 1. Map of sites sampled for stem taper.

GIS plot	Age, BH	SI (ft, 50 yrs)	Foliage retention (yrs)	DBH/QMD
1	31.4	106.9	1.8	1.31
3	27.9	138.1	2.2	1.26
6	37.8	137.4	1.9	1.02
7	33.7	138.4	2.7	1.24
16	28.3	122.7	1.4	1.28
18	30.3	143.7	2.0	1.05
20	40.1	121.7	1.8	1.18
27	28.9	122	2.1	1.19
32	27.8	132.2	2.6	1.17
35	30.4	131.2	2.1	1.24
36	35.2	126.3	2.0	1.11
39	30.9	135.1	1.3	1.08
40	37.6	110.5	2.0	1.00
54	25.6	133.8	3.5	1.18
55	37.3	126.3	2.4	1.12
58	27.3	140.1	3.2	1.24
101	32.1	101.7	1.5	1.45
122	28	149.6	2.1	1.33

Table 1. Descriptive statistics of the 18 SNC sites sampled for tree taper.

Methods

Measurements

Eighteen stands were chosen from among former SNCC GIS plots (Maguire et al. 2011), distributed across the range of foliage retentions (FR) estimated in 2008 (table 1; fig. 1). The sample included four plots with the greatest FR, the four with the lowest FR, and the others were distributed across the FR distribution. In each stand, 5 undamaged and unforked trees were selected for stem form analysis. This selection focused on trees previously rated for SNC, thereby being limited to trees larger than average (mean DBH/QMD=1.19; standard deviation=0.20). The sample targeted the two largest dbh SNC rating trees, a tree approximately equal to quadratic mean diameter, and two other trees (larger than QMD) distributed across the diameter distribution. Chosen trees were measured for dbh, height, and height to lowest live branch (fig. 2). In addition to a stump disk (at 0.15 m of height), and a dbh disk (at tree tag or 1.37 m of height), disk height and diameter outside bark (dob) were recorded for approximately

15-20 disks per tree (the middle of approximately every other interwhorl segment). In the lab, disks were measured for DIB on two axes: the largest diameter and the perpendicular diameter. The DIB was recorded as the geometric mean of the two diameters.

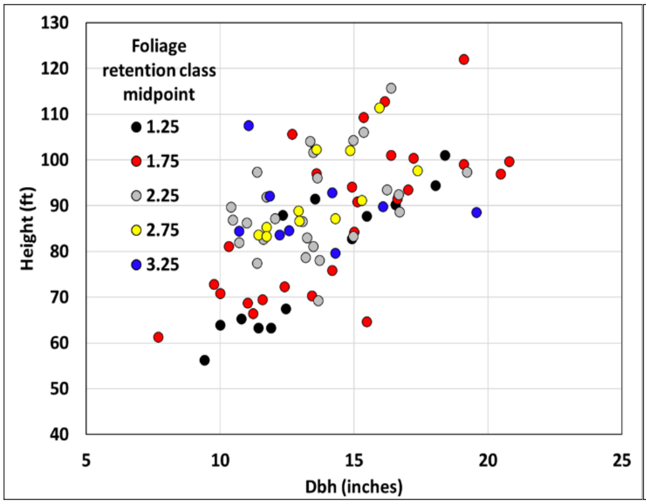

Figure 2. Height vs. Dbh in 2015 for trees sampled for the SNC taper analysis.

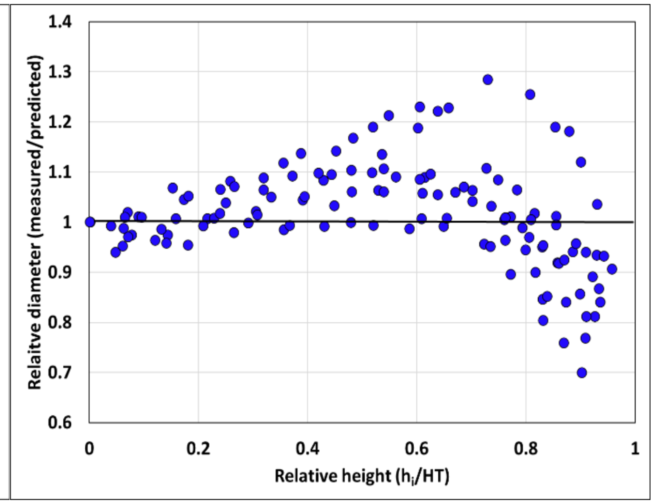

Figure 3. Relative diameter (measured dib vs. predicted dib) vs. relative height for the 9 trees from uninfected plots (FR≥3 yrs). Predictions were made with the Hann (2011) taper equation.

Analysis

Because the taper equation used within the ORGANON volume DLLs (Hann 2011) does not fit the healthy trees of the SNC taper dataset well (fig. 3), it was decided to predict the effect of SNC on stem taper as a modifier of a separate healthy-tree prediction equation. The first step was to fit a taper equation to the nine trees and 144 disks of the trees considered free of SNC (foliage retention ≥ 3 yrs), and the second step was to fit an equation that would predict the modifier: the ratio of the measured upper stem diameters of infected trees and the upper stem diameters predicted from the healthy tree equation.

$$MOD = DIB_{\text{SNC, measured}} / DIB_{\text{SNC, predicted from healthy tree eqn.}}$$

This modifier would be applied within ORGANON to modify the predicted upper stem diameters used to calculate Scribner and cubic volume outputs within infected stands, where:

$$DIB_{\text{ORGANON}} = MOD \cdot DIB_{\text{Hann (2011)}}$$

The Kozak (1988) variable exponent model form was found to be the best fit for the original SNC stem taper equation (Mainwaring et al. 2016) and was used for the two abovementioned equations as well.

Results and Discussion

The relative diameters of healthy trees within the SNC dataset were predicted with the following equation:

$$Y_{healthy} = X^{a0 + a1 \cdot z^2 + a2 \cdot z^{0.5} + a3 \cdot \exp(z) + a4 \cdot \frac{DBH}{HT}} \quad [1]$$

where: $Y_{healthy} = dib_i / DIB_{BH}$

$X = (1-(z^{0.5}))/(1-((1.37/HT)^{0.5}))$
z= relative height (h_i/HT)
DBH= diameter at breast height (cm)
HT = tree top height (m)
dib_i= diameter inside bark at height i (cm)
DIB_{BH}=diameter inside bark at breast height (cm)

The SNC modifier, the ratio of measured upper stem diameters on infected trees to their predicted values from equation [1], was predicted with the following equation:

$$MOD = X^{\left(FRI \cdot \left(b1 \cdot z^2 + b2 \cdot \log(z) + b3 \cdot \frac{DBH}{HT}\right)\right)} \quad [2]$$

where: MOD = $DIB_{SNC,\ measured} / DIB_{SNC,\ predicted\ from\ eqn.\ [1]}$
FRI = $(1-\frac{FR}{3})$ where if FR>3, FR = 3

Parameter estimates and standard errors for equations [1] and [2] are presented in table 2.

Equation	Parameter	Estimate	SE
1	a_0	-4.6371	0.714
n=144	a_1	-5.6761	0.9276
wt=$dib_i^{-0.5}$	a_2	-4.6332	0.4747
wMSE=0.000152	a_3	5.7691	0.775
	a_4	0.1527	0.0148
2	b_1	-0.3102	0.0338
n=1206 wt=$dib_i^{1.5}$	b_2	-0.146	0.014
wMSE=0.4135	b_3	0.1077	0.0158

Table 2. Parameter estimates and SE's for equations [1] and [2].

Equation [2] estimated that the upper stem diameters of the most infected trees have upper stem diameters ~10% lower than healthy trees of the same dbh and top height. For a given foliage retention, these differences are predicted to be greater for the larger, more dominant trees (those with a larger dbh:height ratio, fig. 4). Importantly, the biggest differences are at relative heights between 0.4 and 0.5, which is near the scaling diameter of a forty-foot butt log in intensively managed stands harvested at typical rotation ages. Above ~70% of total height, equation [2] predicts larger diameters for infected trees. While this difference was apparent within the data, for the purposes of calculating volumes within ORGANON it is of little consequence, being about the relative height of typical merchantable top diameters (fig. 5).

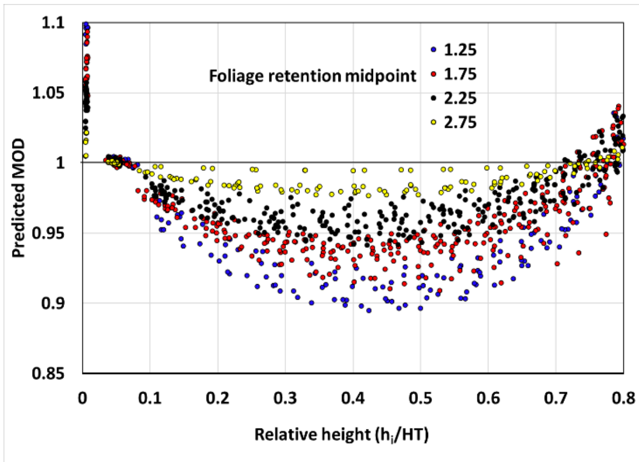

Figure 4. Predicted values of MOD from equation [2] for input values within the modeling dataset, color coded by foliage retention midpoint.

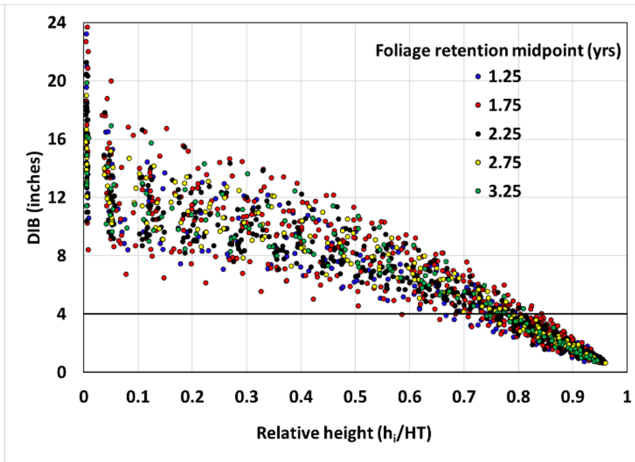

Figure 5. Measured values of dib vs. relative height for different foliage retention classes. Black line at 4” dib emphasizes typical merchantable top diameter.

Applying this taper modifier within ORGANON results in lower estimates of standing cubic and Scribner volume for treelists near rotation age, with absolute differences of between 5 and 10% at low values of foliage retention (fig. 6).

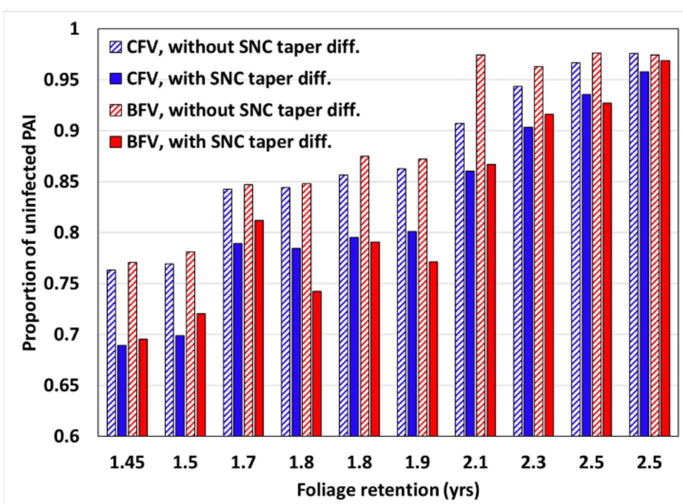

Figure 6. ORGANON-estimated standing cubic and Scribner volumes from ten treelists (aged 30-42 yrs) with different levels of foliage retention. Striped columns show volumes that do not account for SNC effects on taper; solid columns do account for SNC-related taper differences.

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Effect of Swiss Needle Cast Infection upon Diameter and Height Increment of Douglas-fir Trees

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Abstract

Modifiers to account for the negative effect of Swiss needle cast (SNC) infection on diameter and height increment within ORGANON were estimated using data from the Swiss needle cast Coop's new research plot network. Using a similar model form to previous iterations of SNC-modifiers, diameter and height increment were estimated to decrease at foliage retentions below about 3.0 years. Diameter and height increment at a foliage retention of 1.0 year were both estimated to be ~70% of that expected on uninfected plots. The implied growth loss is similar to what has been previously estimated for diameter, but significantly larger than what has been previously estimated for height, the result of use of an adjusted site index to account for lost height development within infected plots.

Introduction

Swiss needle cast (SNC) is a disease caused by the endemic foliar fungus *Nothophaeocryptopus gaeumannii*. The disease leads to significant increment losses in Douglas-fir through two primary mechanisms. The fungus grows into needles, eventually occluding stomates with fruiting bodies and decreasing stomatal conductance and rates of CO_2 assimilation (Hansen et al. 2000; Manter et al. 2000). Where infections are sufficiently severe, this ultimately causes premature loss of older foliage, reducing mean foliage retention to as little as one year and volume increment by as much as 50% (Maguire et al. 2011). The increment impact of SNC can be estimated in numerous ways, but all depend on the relationship between some index of SNC severity and observed increment relative to that expected in the absence of SNC. Foliage retention, the number of annual cohorts of foliage retained, is currently the primary index of SNC severity (Hansen et al. 2000). Observed increment infected permanent plots depart considerably from expectations based on a regional increment model (ORGANON; Hann 2006), especially below a stand average foliage retention of 2.5 years (Weiskittel and Maguire 2004). Increment predictions from individual-tree models like ORGANON have been adjusted at the stand level by the ratio of observed to expected increment, conditional on initial SNC severity for the stand. Although this approach provides a first approximation of increment losses, it does not account for possible changes in long-term stand dynamics imposed by SNC and, therefore, may not perform well for estimating future dimensions of individual trees and associated economic impacts of SNC. Data have now accumulated to develop modifier equations for diameter and height increment of individual Douglas-fir trees. The goal of this study was to improve the ability of forest managers in the Douglas-fir region to predict the influence of SNC on future stand inventories, allowable cut, and economic productivity. The specific objective of this study was to develop a system for determining increment modifiers that predict the effect of SNC on both diameter and height increment of individual trees. The modifiers were tested within the public ORGANON model.

Methods

Study Sites

Data for this analysis were contributed by the Swiss Needle Cast Cooperative at OSU from their new Research Plot Network (RPN, Ritokova et al. 2015). One hundred and six plots were installed over three years between 2013 and 2015 on predominately Douglas-fir sites to investigate the influence of SNC on increment losses. Plots were established across a range in topographic positions and SNC severity. Latitudes ranged from the Oregon-California border (42.06°N) to SW Washington (46.65°N), and from the Ocean (124.41°W) to 35 miles inland (123.27°W), and elevation ranged from 150 to 2500 ft above sea level (fig. 1).

The first five-year remeasurement of the RPN was recently completed. The plots were distributed amongst a 6x4 cell sampling matrix (6 evenly distributed north-south sites and 4 east-west zones) to ensure an even geographic distribution. Site indices (Bruce 1981) were estimated from height-age pairs and ranged from 89-172 ft (50 yrs) and foliage retentions ranged from 1.15 to 3.90 years (Table 1).

Although earlier analyses of SNC effects on diameter and height increment were based on four studies whose measurements were taken between 1998 and 2008, stand-level cubic volume growth losses estimated from that dataset were significantly greater than that estimated more recently from the RPN. Both datasets are believed to represent the population of Coast Range Douglas-fir plantations present during their periods of measurement, but in the 15 years prior to the

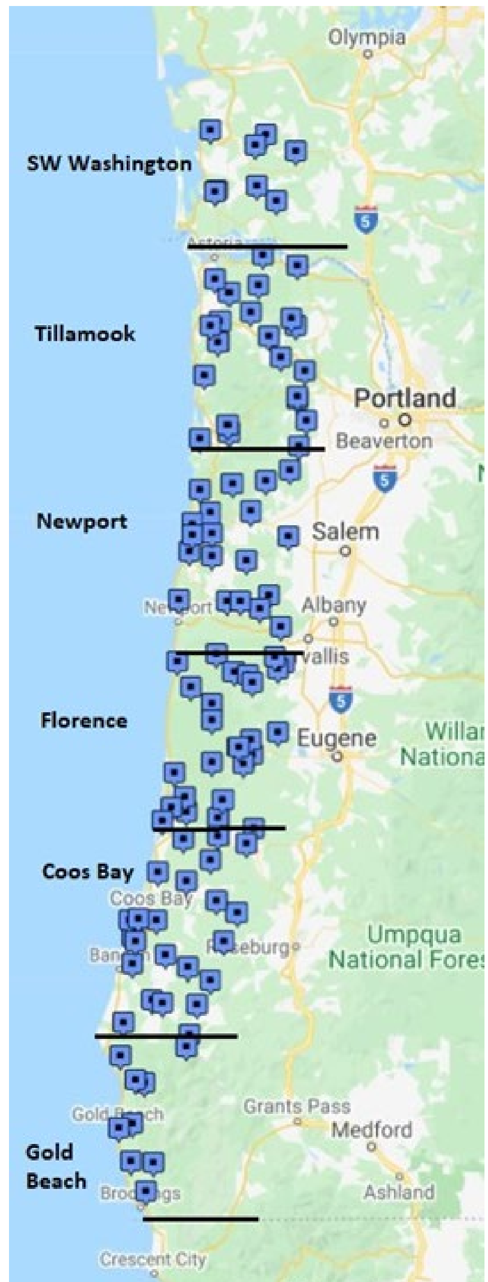

Figure 1. Map of SNCC RPN sites.

establishment of the RPN, landowners of SNC-impacted stands recognized slow tree growth in their holdings, harvesting many merchantable stands and in some cases liquidating pre-merchantable stands and replanting to western hemlock or other non-susceptible species. Consequently, it is believed that the population of infected stands is different now than in the earlier period, and that the RPN better represents what currently exists. Accordingly, this analysis was based on RPN data only.

Plot and Tree Measurements

All trees with diameter at breast height (DBH) ≥2 inches were tagged on 0.2 ac permanent plots. At plot establishment and during the remeasurement, DBH was recorded for all trees, and total height (HT) and height to lowest live branch (HLB) were measured on a subsample of Douglas-fir trees across the diameter range. In the spring prior to the first growing season of growth, five to ten dominant or codominant trees were scored in April or May for SNC severity. These trees were climbed, and foliage retention was estimated on the largest four-year old lateral branch of the southernmost primary branch from the whorl located closest to the center of the live crown. Plot-level retention was the average from each of the sampled trees.

Diameter and height increments for each tree in the data set were predicted for each plot and measurement combination using the SMC version of the ORGANON growth and yield model (Hann 2011). In a few cases, measured growth periods didn't correspond to the five-year increments of ORGANON, in which cases linear interpolation of diameter and height increment was employed.

Site index

SNC-related modifications of model-estimated diameter and height increment are sensitive to estimates of site index, given the centrality of site index within the diameter and height increment equations of ORGANON. Furthermore, because the dominant height of trees on SNC-infected plots have experienced previous height increment losses as a result of SNC, determination of site-expressed dominant height, and thus site index, is a moving target. Using the site index estimated from SNC-infected height-age pairs without any adjustment would result in an underestimation of growth loss, because the dominant heights upon which SI was based would be lower than that expected in the absence of SNC.

A simple means of estimating the SNC-free site index, here termed SI_{adj}, was accomplished under the assumption that the trees of this plot network had experienced the same level of foliage retention throughout their lifetimes, and that the relationship between growth loss and dominant height could be properly described with the ORGANON-height modifier estimated by Hann et al. (2014):

$$\mathrm{SI_{adj}} = \frac{SI_{measured}}{HTMOD_{Hann(2014)}} = \frac{SI}{(1+exp(-1.80657-0.0855 \cdot FR^3)}$$

This relationship elevated estimates of SI on infected plots as shown in figure 2.

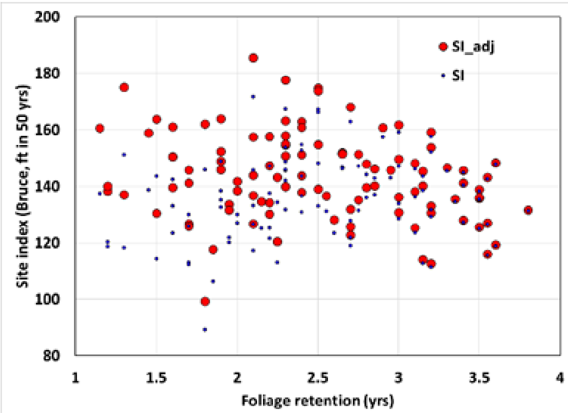

Figure 2. Relationship between SI and foliage retention, with and without adjustment.

Table 1. Site and zone level statistics based on six north-south sites and 4 east-west zones shown in fig. 1.

SITE	ZONE	FOLRET (yrs)	SI (ft, 50 yrs)	SI_{adj} (ft, 50 yrs)	BH_Age (yrs)	TPA_DF	%BA_DF
SW Washington	5-15 mi.	1.9	126.4	138.8	13.7	398	75.3
	15-25 mi.	3.0	129.9	132.6	12.5	395	93.5
	25-35 mil	3.1	134.7	136.8	16.3	338	94.7
Tillamook	0-5 mi.	1.8	126.5	140.6	17.3	303	91.0
	5-15 mi.	1.7	124.8	140.3	12.8	401	99.6
	15-25 mi.	2.7	136.3	142.9	21.2	307	91.0
	25-35 mi.	3.2	130.8	133.0	15.8	322	95.7
Newport	0-5 mi.	1.8	127.4	142.1	17.6	307	81.0
	5-15 mi.	2.3	124.5	132.9	15.5	400	97.3
	15-25 mi.	3.0	145.0	147.5	17.5	299	98.5
	25-35 mi.	3.2	137.0	139.2	12.8	348	94.2
Florence	0-5 mi.	1.6	126.3	142.3	17.0	315	88.5
	5-15 mi.	2.0	142.9	155.7	14.3	448	99.1
	15-25 mi.	2.8	144.8	150.3	17.6	301	94.0
	25-35 mi.	3.1	146.8	150.3	16.4	434	98.6
Coos Bay	0-5 mi.	2.1	121.5	130.8	15.0	388	87.6
	5-15 mi.	2.3	146.5	155.0	19.0	272	98.5
	15-25 mi.	2.6	154.4	160.9	13.6	394	99.4
	25-35 mi.	2.8	143.8	149.1	17.8	352	96.8
Gold Beach	0-5 mi.	2.6	127.3	134.0	20.2	333	92.4
	5-15 mi.	2.5	130.7	137.6	14.3	657	96.7
	15-25 mi.	3.3	129.5	130.6	18.5	273	99.5

Data Analysis

The general approach used to characterize the impact of SNC upon increment (Δ) was to use the predictions of increment (PΔ) from SMC-ORGANON as expected stand development with no influence of SNC and then adjust PΔ with a modifier (MOD) in order to estimate the direct effect of SNC upon increment:

$$\Delta = P\Delta \cdot MOD$$

MOD equations for ΔD and ΔH were developed from only those trees with measured HT and HLB.

Because ORGANON was developed using a comprehensive database from a much broader geographical region than the Swiss needle cast population represented by the RPN, calibration factors (cal) on PΔD and PΔH from SMC-ORGANON were calculated using the SNC data sets to provide a more accurate expectation from which to estimate direct effects of SNC. The calibration factors were estimated using trees with measured HT and HLB from stands judged to be healthy (foliage retention ≥ 3 yrs). Separate calibration factors were estimated for uninfected trees within each of the six latitudinal sampling zones (table1, fig. 1). Observed individual tree increments were regressed on predicted increments from SMC-ORGANON using unweighted, simple linear regression through the origin. The regression models were as follows:

$$\Delta D = cal_D \cdot P\Delta D \qquad [1]$$

$$\Delta H = cal_H \cdot P\Delta H \qquad [2]$$

where: ΔD and ΔH were observed diameter and height increment, respectively; cal_D and cal_H were the estimated slope parameters defining the calibration between ΔD and PΔD and ΔH and PΔH, respectively; and PΔD and PΔH were defined above.

The modeling data sets for estimating parameters in the MOD prediction equation were then developed by applying the calibration factors to PΔD and PΔH values from SMC-ORGANON for trees on plots considered to be "impacted" by SNC and then combining these simulated data with measured ΔD, ΔH, and FOLRET. An SNC multiplier is expected to range between zero and one, with a value close to one for trees expressing little impact of SNC (e.g., Garber et al., 2007). The following model forms were used for the ΔD and ΔH modifiers:

$$MOD_D = \frac{\Delta D}{P\Delta D_{cal_D}} = 1.0 - e^{\left(b_0 + b_1 FOLRET^{b2}\right)} \qquad [3]$$

$$MOD_H = \frac{\Delta H}{P\Delta H_{cal_H}} = 1.0 - e^{\left(b_0 + b_1 FOLRET^{b2}\right)} \qquad [4]$$

where: MOD_D and MOD_H were the modifiers for estimating diameter and height increment, respectively, of a potentially SNC-impacted tree as a proportion of the diameter and height increment predicted by SMC-ORGANON for a similar tree unimpacted by SNC; FOLRET was initial foliage retention in years; and b_0 and b_1 were parameters estimated from the data. This model form was used by Zhao et al. (2012) and it is a generalization of the model form previously used by Garber et al. (2007).

Both Garber et al. (2007) and Zhao et al. (2012) estimated the parameters of equations [3] and [4] using tree-level data. However, FOLRET is measured at the plot-level for each measurement, and, as a result, parameterizing equations [3] and [4] using tree-level data will underestimate the size of the standard errors of the parameters. Later analysis by Hann et al. (2014) found that standard errors resulting from the plot-level fits were substantially bigger than those from the tree-level fits (Table 1), recommending plot-level fits to avoid mistaken conclusions about the significance of the parameters. As a result, plot-level fits were chosen for this analysis.

Results and Discussion

Of the individual "healthy" Douglas-fir trees with measured HT and HLB, a total of 1,180 trees were available for estimating the diameter and height calibration factors. These multipliers were then applied to PΔD and PΔH for trees measured on the "infected" plots. This resulted in a total of 2,859 calibrated PΔD and 2,726 calibrated PΔH values for SNC-impacted Douglas-fir trees with measured HT and HLB. These trees were used to create the plot-level modeling data sets, made up of 72 observations with a dependent variable calculated on the plot level by dividing the sum of diameter and height increments on infected plots by the sum of their calibrated, model-estimated values.

Equations [3] and [4] were estimated using weighted regression (weights: [3] MOD_D^{-1}; [4] $MOD_H^{-0.5}$); the resulting parameter estimates and their standard errors for equations [3] and [4] for SMC-ORGANON are found in Table 2. Both parameters were significantly different from zero ($p \leq 0.05$) for both modifier equations for both models. A graph of the modifier equations across FOLRET is shown in Figure 3.

	SMC-ORGANON	
Parameter	ΔD	ΔH
b_0	-1.0596	-1.1252
	(-0.4291)	(-0.2179)
b_1	-0.2104	-0.1332
	(-0.1035)	(-0.0375)
b_2	2.5	3
	(NA)	(NA)

Table 2. Parameter estimates and their standard errors (in parentheses) for the application of Equations [3] and [4] to the diameter increment (ΔD) and height increment (ΔH) data sets.

The predictors of MOD for ΔD and ΔH produced reasonable behavior over the observed range of initial foliage retention and were approximately equal for both components of tree increment (Fig. 3).

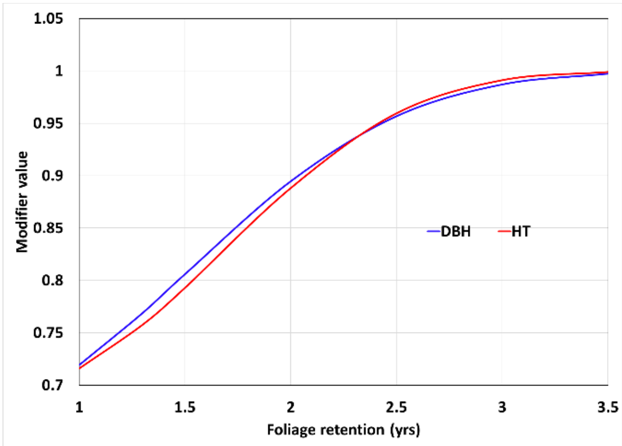

Figure 3. Diameter and height increment modifier values vs. foliage retention for SMC-ORGANON.

The predicted height increment loss of ~29% at a foliage retention of 1.0 years is nearly double that predicted by Hann et al. (2014). This difference is due to the use of adjusted site index to account for the loss of height increment within infected stands. It is unknown what the actual loss of height within these plots has been since their establishment, due both to the unknown pattern of height loss relative to age in general, and the unknown variation of foliage retention over time within the plots more specifically. Use of Hann et al.'s 15% maximum growth loss (2014) to adjust the site index of infected plots is an approximation, though the fact that it results in a slopeless relationship between SI and FOLRET for sites with a foliage retention <3.5 yrs (p=0.20) for the new plot network (fig. 2) and the combined sites of the new plot network and the sites measured between 1998 and 2008 (p=0.87) suggests use of this adjuster is not quantitatively inappropriate.

An earlier analysis by Garber et al. (2007) included the addition of BAL as an explanatory variable in equations [3] and [4]. Hann et al. (2014) explored this option but found opposite effects of BAL within the diameter and height modifiers, thereby concluding it was biologically unreasonable, and didn't make sense to include. Use of BAL was also attempted in the current analysis, and more subordinate trees were estimated to have more ORGANON-estimated diameter increment loss at a given level of foliage retention. However, comparisons of the long-term effects from using modifiers with or without BAL in post-analysis simulations resulted in small differences in projected diameters, and a slightly poorer fit to actual increment on four validation plots simulated for twenty years. Accordingly, the reduced model without BAL was chosen.

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Swiss needle cast transect plots in the Oregon Cascade foothills

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Background

Forty-seven disease monitoring transects were established in the Oregon Cascades foothills in 2017. The sites are located in young Douglas-fir plantations between the ages of 13 and 27 years on SNCC member lands: Weyerhaeuser, Cascade Timber Consulting (CTC), Oregon Department of Forestry (ODF), and a private landowner, Melcher Logging and Timber Harvesting Inc. (fig. 1). In 2020, for the fourth consecutive year, the transects were evaluated for Swiss needle cast (SNC) severity.

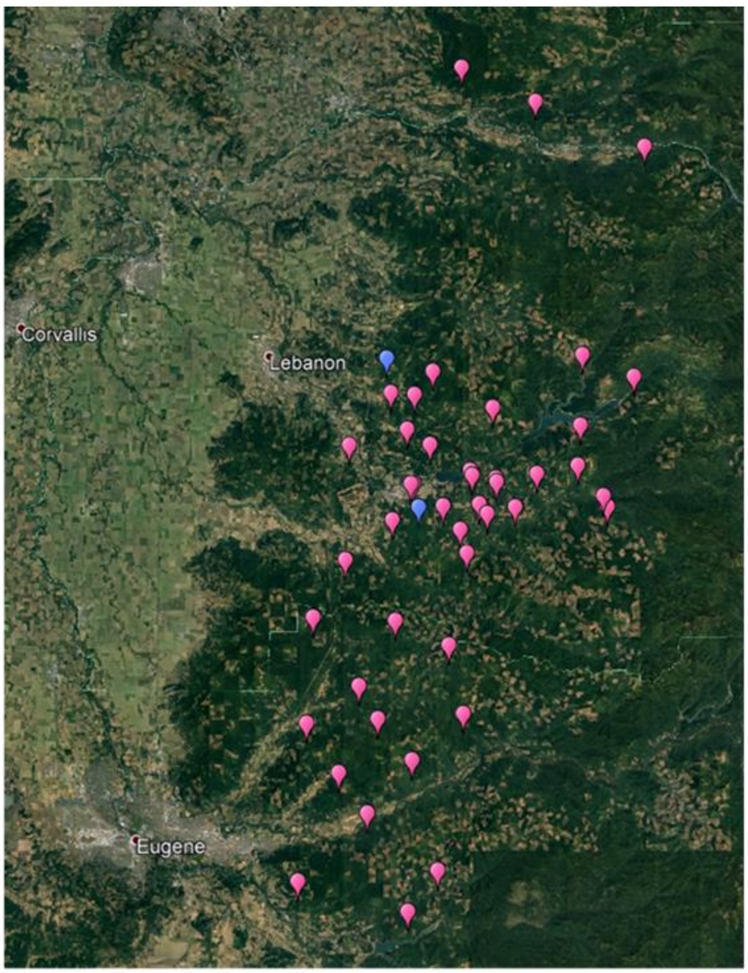

Figure 1. Transect locations in the Oregon Cascade foothills.

Sampling methodology was described in detail on page 45 in the 2018 SNCC annual report.

In the late summer of 2020, a series of fires burned portions of the Cascades in Oregon, including areas where SNCC transects were located. One transect near Mill City burned as well as a yet unknown number of transects east of Eugene. We are still evaluating the damage caused by these fires.

Forty-four transects were monitored for foliage retention, of which 32 were evaluated for severity. We continue to monitor weather conditions in two transects near Sweet Home, Oregon (denoted with blue markers, fig.1).

2020 Results

Although the pathogen was present in some sites classified as healthy, disease symptoms were minimal. The average three-year change in foliage retention was positive, with very few trees (<5% showing declines in foliage retention over the period (fig. 2). During the same period, ~22% of the trees were found to have no change in foliage retention.

The results were not as clear for the disease severity index. Those trees showing no SNC presence in 2017 tended to show increasing disease, being 12 times more likely to get worse than not. Conversely, for the trees in the worst condition in 2017 (severity index of 3), about half got better, and half stayed the same. For trees with a severity index of 1 in 2017, 19 got better, while 27 got worse. Those trees with a severity index of 2 in 2017 mostly got better, being almost ten times as likely to improve (fig. 3). Overall, 90 trees exhibited a diminished presence of pseudothecia, while 48 had an increased presence. These results suggest that while the improvement in foliage retention is positive and overall disease severity is lower, the disease remains present in significant quantity.

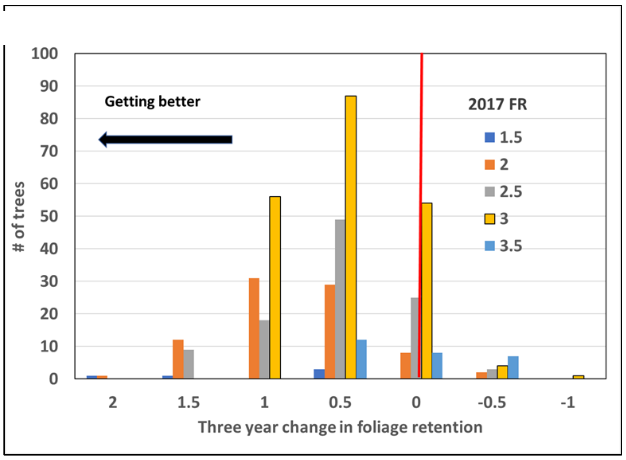

Figure 2. Tree-level three-year change in foliage retention, measured in the spring of 2020.

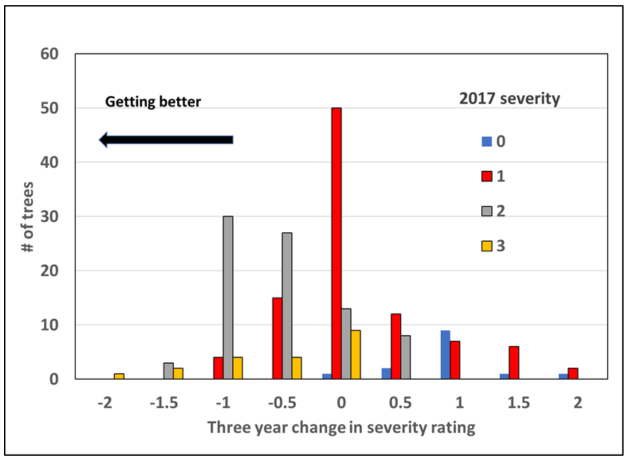

Figure 3. Tree-level three-year change in disease severity index, measured in the spring of 2020.

Biotic and spatial effects structure the foliar microbiome of Douglas-fir

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Host tree genetic and environmental drivers of foliar fungal community composition have been previously documented in Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*), yet little is known about the factors structuring co-occurring oomycetes, which include major plant pathogens. In this study, we sampled senescing needles from Douglas-fir trees in three coastal Pacific Northwest (PNW) common gardens as part of the US Forest Service's Douglas-fir Seed Source Movement Trial (SSMT), a long-term reciprocal transplant experiment (Fig. 1). We used fungal (ITS2) and oomycete (*rps10*) metabarcoding to characterize both groups of organisms in Douglas-fir foliage. Needles were also cultured in oomycete-specific media to identify and describe novel oomycetes.

We found evidence for both host genetic and spatial effects on fungal community composition. Fungal communities were structured most heavily among sites (Fig. 2, Table 1A), and to a small extent among half-sibling families within sites (Table 1B-D). Trees' landscape-wide provenance, or seed source region (SSR), had no impact on fungal community composition. Oomycete communities were dominated by a single Clade 9 *Phytophthora* OTU (60% of oomycete reads) that was negatively correlated with fungal rarefied richness overall, as well as with the presence of *Nothophaeocryptopus gaeumannii*, the causal agent of the foliar disease Swiss needle cast (SNC) (Table 2).

18 oomycete cultures were isolated from the needles of 18 different trees, primarily from Nortons, the northern Oregon coast site (Fig. 3). Sanger sequencing and maximum likelihood (ML) analyses of ITS, COI, and *rps10* genes revealed that all isolates were closely related and clustered within the genus *Pythium*.

Our results demonstrate that while oomycetes may be less diverse than fungi within conifer needles, their ecological roles, both within trees and across the landscape, are far from being understood. Their putative negative relationship to fungi suggests that the two groups of organisms may occupy similar functional niches within needle tissue and may be competitors. These findings highlight the importance of understanding the biotic effects that may influence overall tree health.

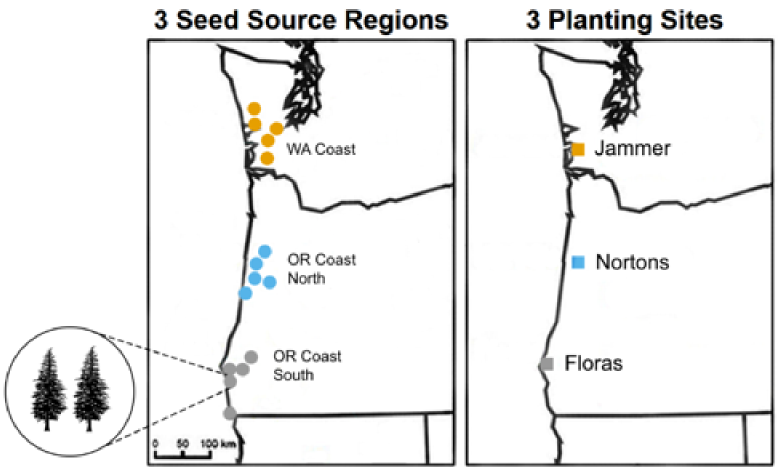

Figure 1 Locations of seed source region (SSR) (left) and study sites (right). Seed was collected from 2 maternal trees (inset) in each of 5 locations within each SSR. Each SSR was composed of 10 lines of half-siblings (families). Adapted from Wilhelmi et al. (2017).

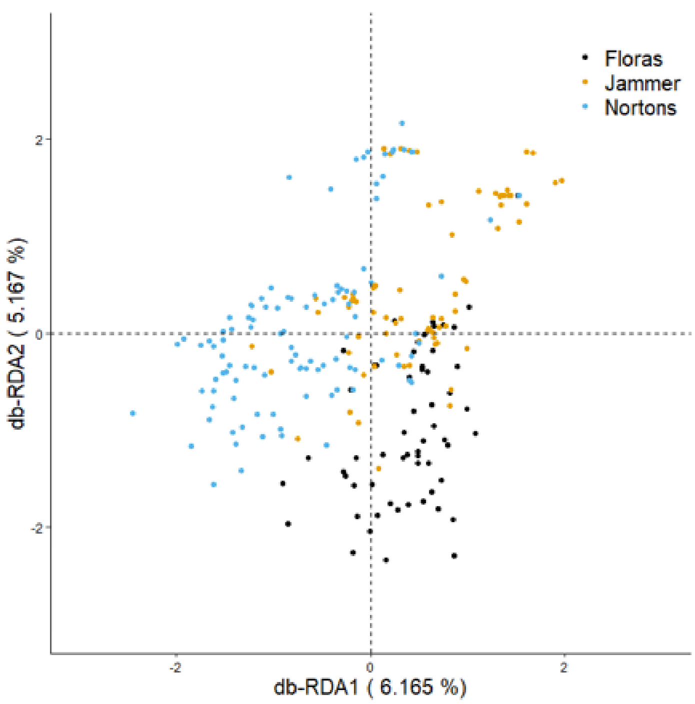

Figure 2 Distance-based redundancy analysis (db-RDA) ordination of foliar fungal communities constrained by site based on Bray-Curtis dissimilarity. Each point represents the fungal community of a single tree's pooled needles. Axes scores show the percentage of total cumulative variation explained by that axis, for a total of about 11.3%.

A) All sites

Source	df	Pseudo-F	p(perm)
Site	**2**	**4.2251**	**0.0001**
SSR	2	1.2531	0.1455
Block(Site)	**9**	**1.7918**	**0.0015**
Family(SSR)	12	1.0818	0.3233
Site x SSR	**4**	**1.0433**	**0.0238**
Site x Family(SSR)	**24**	**1.4032**	**0.0008**
Block(Site) x SSR	**18**	**1.3398**	**0.0064**
Residuals	174		
Total	245		

B) Floras

Source	df	Pseudo-F	p(perm)
SSR	2	0.94073	0.5973
Block	3	1.3396	0.1693
Family(SSR)	**12**	**1.3955**	**0.0246**
SSR x Block	6	1.3421	0.08
Residuals	18		
Total	58		

C) Jammer

Source	df	Pseudo-F	p(perm)
SSR	2	1.3518	0.1574
Block	**3**	**3.0815**	**0.0048**
Family(SSR)	**12**	**1.661**	**0.0181**
SSR x Block	6	1.1081	0.3502
Residuals	31		
Total	81		

D) Nortons

Source	df	Pseudo-F	p(perm)
SSR	2	0.73897	0.9068
Block	3	1.2427	0.2846
Family(SSR)	**12**	**1.4372**	**0.0323**
SSR x Block	6	1.4061	0.0688
Residuals	45		
Total	104		

Table 1 PERMANOVA results of location and host lineage effects on Bray-Curtis dissimilarity of fungal communities **A)** across all three sites, and **B-D)** within individual sites. Location effects: Site, Block nested in Site. Host lineage effects: SSR, Half-sibling Family nested in SSR. The highest order terms (Block[Site] x Family[SSR] across sites and Block x Family[SSR] within sites) were excluded because it lacked replication at the lowest level due to dead or missing trees throughout the sites. Significant terms are bolded.

A) Response: Presence/absence of *Phytophthora* sp.

	Estimate	Std. Error	z value	*p*
Intercept	0.6957	0.2005	3.47	0.00052
Fungal richness (Chao)	-0.3844	0.1389	-2.767	0.00565

B) Response: Presence/absence of *N. gaeumannii*

	Estimate	Std Error	z value	*p*
Intercept	1.393	0.458	3.047	0.002
***Phytophthora* sp.**	-0.654	0.309	-2.117	0.03

Table 2 Output of mixed-effect logistic regressions of **A)** fungal rarefied richness (Chao) predicting the presence or absence of the dominant *Phytophthora* OTU including the within-site random effects Block and Family, and **B)** the presence or absence of the dominant *Phytophthora* OTU

predicting the presence or absence of *N. gaeumannii*, the SNC pathogen including the among-site random effects Site and SSR.

Figure 3 *Pythium* mycelia emerging from a needle plated in oomycete-selective media (CARP).

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Disease Distribution, Severity and Epidemiology

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