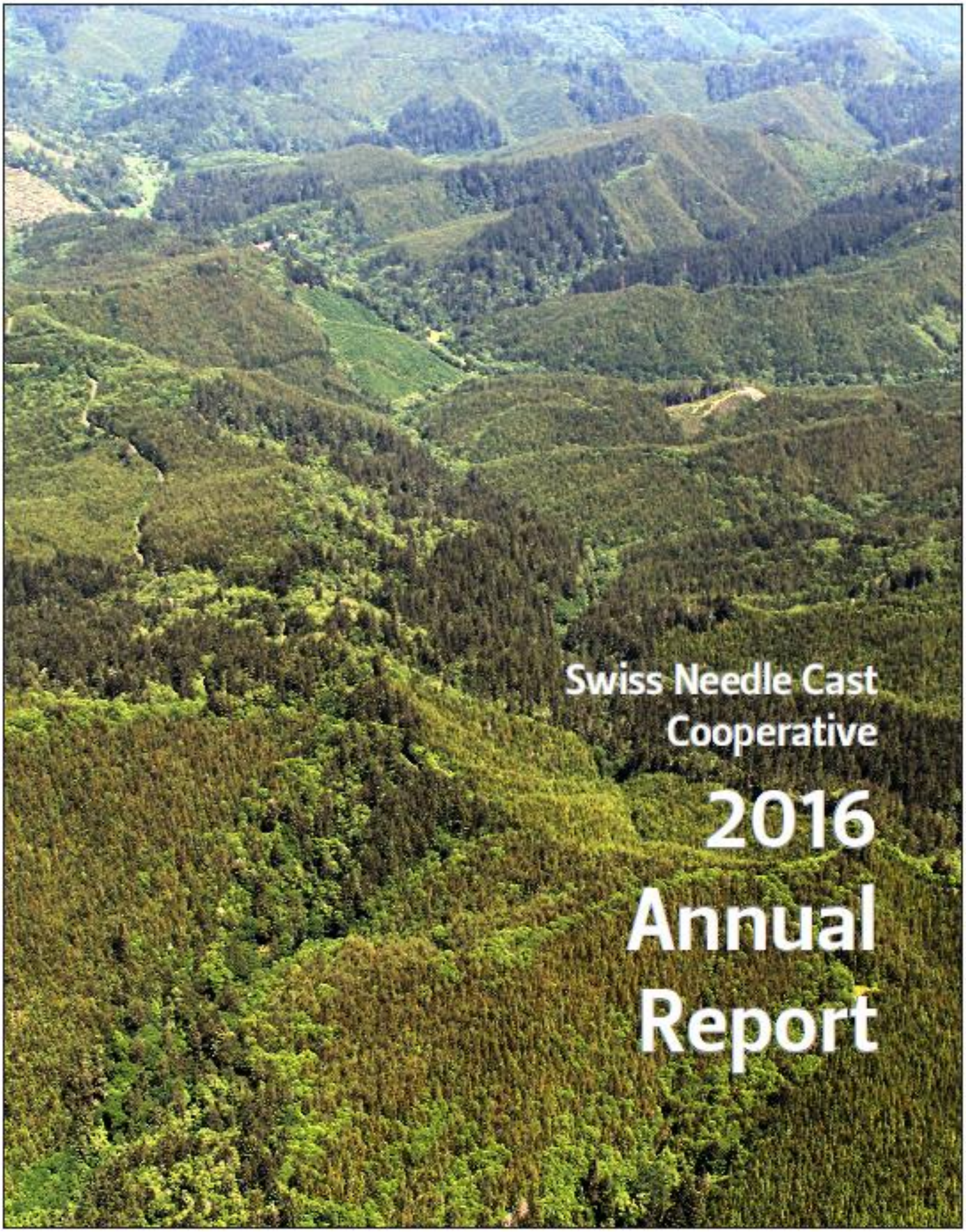
Oregon State University | College of Forestry



Swiss Needle Cast Cooperative Staff

Dave Shaw – Director and Associate Professor of Forest Health

Gabriela Ritóková – Assistant Director

Members of the Swiss Needle Cast Cooperative

Bureau of Land Management

Cascade Timber Consulting

Oregon Department of Forestry

Starker Forests

Stimson Lumber

USDA Forest Service

Weyerhaeuser Corporation

Edited by Gabriela Ritóková and Dave Shaw
Cover photo by Wyatt Williams, ODF

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SNCC Income Sources and Expenditures: 2016

Income

Membership dues	70,000
Oregon State Legislature	95,000
Gift	32,000
Carry-over	-1,502
Total 2016 Budget	**$195,498**

Expenditures

Salaries and wages	188,455
Travel	1,612
Operating expenses	13,450
Contract Work	9,000
Materials and Supplies	725
Indirect Costs	27,721
Total 2015 Expenditures	**$240,963**

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, *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.

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January 25, 2017

To: Swiss Needle Cast Cooperative Members

From: David Shaw, Director, and Gabriela Ritóková, Assistant Director
Swiss Needle Cast Cooperative, College of Forestry, Oregon State University

Dear Members,

Gabriela Ritokova and I are pleased to present the 2016 Swiss Needle Cast Cooperative Annual Report. Our collaborations with partners in Oregon and Washington are bearing fruit, and we have a pretty good idea of the landscape distribution of disease from Northern California into British Columbia, Canada. Through the Western International Forest Disease Work Conference (WIFDWC), we collaborate and discuss the SNC epidemic, and partners in British Columbia have sought some support. Danny Norlander, Oregon Department of Forestry Monitoring and Survey Specialist, went to BC and did a training. The region of interest is the Fraser River Valley E of Vancouver, a very high rainfall area, where an official survey may take place in spring 2017. WIFDWC will meet in British Columbia this year on Vancouver Island, so we will have an opportunity to follow up with colleagues concerning the status and management of SNC and other important diseases, such as the pine foliage disease red band needle blight and cedar leaf blight, both of which are major issues in BC.

The Annual Report includes aerial survey data for Oregon and Washington in 2016. The acres effected with visible symptoms of SNC in Oregon has plateaued for the past 3 years, but is hovering around 550,000 acres. The plateau is good news, and visible acres effected was down significantly in 2016 for Washington. We are hopeful this season's cold winter weather will negatively influence the disease, as winter temperature is a key epidemiological factor.

There are four graduate student reports in the 2016 SNCC Annual Report. Sky Lan is comparing microclimate and SNC infection severity between adjacent old, mature, and young trees, as well as collaborating with Jeff Hatten, Gabi and I to investigate the link between soil N, foliage N, and disease. Nick Wilhelmi completed his study using the USFS, PNW (Connie Harrington, Brad St. Clair) reciprocal planting trial, and reports on strong seed source interactions with both SNC and Rhabdocline foliage disease. He shows that moving seed sources from high elevation to low elevation, or dry environments into wet environments, increases likelihood of disease. He also showed that local seed sources consistently had lower disease expression. In addition, he found that wherever *Phaeocryptopus gaeumannii* is found, it equally infects all Douglas-fir. However, some seed sources show disease tolerance while others have thin chlorotic crowns, and reduced growth. Therefore, disease expression varies based on seed source.

Patrick Bennett is continuing work on the molecular ecology of *P. gaeumannii*, and investigating the two biotypes, while also attempting a pathogenicity study to determine if one of the biotypes is more pathogenic than the other. Finally, Jonathan Burnett is testing the ability of drone and sensing technology to assess SNC infection in trees.

We are continuing to collaborate with CIPS, and they have recently shown that SNC is influencing taper of Douglas-fir. We also continue to watch other emerging west-side Douglas-fir issues, and have included an update on web blight and red needle cast of Douglas-fir by Jared LeBoldus. Jared also recently received a grant from USFS Forest Health Monitoring to investigate the black stain root disease issue.

Finally, Gabriela completed installation of the SNC Research and Monitoring Plot Network from the California border north into SW Washington and inland 35 miles. The 106 plots now form a significant framework to further investigate epidemiology of SNC, assess growth impacts over a range of infection levels, improve models, and collaborate with others who want to work on well documented sites infected with SNCC, i.e. graduate students Patrick Bennett, Jonathan Burnett, and Sky Lan. In addition, our plot network was set up in collaboration with Jeff Hatten, the forest soil scientist at OSU. We are completing the pseudothecia counting from all these plots, and will have data on soil nutrients, foliage nutrients, foliage retention, and foliage disease severity, thus providing a comprehensive dataset for analysis.

Thank you all for your support of the Swiss Needle Cast Cooperative. We feel strongly that protecting Oregon forests is our mission, and in our case, the resource is west-side Douglas-fir. Although the Swiss needle cast epidemic continues, our ability to manage and understand what is happening is continuing to improve due to our research, monitoring and focus.

Sincerely,

David Shaw Gabriela Ritóková

David Shaw Gabriela Ritóková

2016 Swiss Needle Cast Aerial Survey

Sarah Navarro and Danny Norlander
Oregon Department of Forestry

Survey procedures

The observation plane flew at 1,500 to 2,000 feet above the terrain, following north-south lines separated by 2 miles. Observers looked for areas of Douglas-fir forest with obvious yellow to yellow-brown foliage, a symptom of Swiss needle cast (SNC). Patches of forest with these symptoms (patches are referred to as polygons) were sketched onto computer touch-screens displaying topographic maps or ortho-photos and the position of the aircraft. Each polygon was classified for degree of discoloration as either "S" (severe) or "M" (moderate). Polygons classified as "S" had very sparse crowns and brownish foliage, while those classified as "M" were predominantly yellow to yellow-brown foliage with slightly denser crowns than those classified as "S". The survey area extended from the Columbia River in Oregon south to the California border, and from the coastline eastward until obvious symptoms were no longer visible. We also surveyed a portion of the west slope of the Cascade Range in 2015, from Lane County north through Clackamas County.

Results

The survey was flown on May 5, 6, 9, 10, 11, 20, 24, 2016 and covered 3,671,175 acres in the Coast Range and 662,082 acres in the Cascade Range (figure 1). Symptom development was inline with average years and bud break occurred inline with when the survey is normally flown. Early good weather provided good conditions for the survey and it was only delayed towards the end due to aircraft maintenance issues that required a replacement aircraft to be used. With the replacement plane the final section of the coast range and the Cascades were completed by the end of May.

The survey showed a slight decrease in the area of forest with symptoms of Swiss needle cast compared to the previous 5 years, the first decrease observed in six years. In the Coast Range we mapped 546,243 acres of Douglas-fir forest with obvious symptoms of Swiss needle cast (figure 2). As has been the case for the past several years, the easternmost area with obvious SNC symptoms was approximately 28 miles inland from the coast in the Highway 20 corridor, but most of the area with symptoms occurred within 18 miles of the coast. Figures 3 and 4 show the trend in damage from 1996 through 2016.

In 2016, as in 2015, we extended the survey south through Curry County to the California border even though few symptoms typically are observed south of Port-Orford. In Curry County we mapped only 31 polygons representing 1,276 acres with symptoms, most of them in the Port-Orford area.

In the partial survey of the Cascades Range (Lane, Linn, Marion, and Clackamas Counties), we mapped 2,240 acres of moderate SNC symptoms were detected. A more systematic survey was flown in 2016, compared to 2015, in the Cascades Range in late May.

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 Swiss needle cast occurs throughout the survey area, but discoloration often is not severe enough to enable aerial detection. The total area 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 and severe damage, and coarsely documents trends in damage over time.

Canadian Survey Interest

The British Columbia Ministry or Forestry was interested in conducting a needle cast survey and Danny Norlander traveled to Chiliwack, B.C. To assist in the effort. Norlander provided technical transfer on survey methods, technology, and aerial visible symptoms in early May. There is continued interest in the effects of needle cast in the area and it is likely that Norlander will travel back to Canada in the spring of 2017 for additional cooperation with Provincial counterparts.

Acknowledgements

The survey was conducted by the Oregon Department of Forestry Forest Health and Air Operations sections, and was funded by the Oregon State University Swiss Needle Cast Cooperative, the USDA Forest Service Forest, and the Oregon Department of Forestry. Dan McCarron piloted the ODF plane and Chris DiOrio was the copilot for the plane used as a replacement (Butler Aircraft). Danny Norlander (ODF) is the survey coordinator and primary observer. Other aerial observers were Bob Schroeter (USFS Region 6 FHP), Zack Heath (USFS), Wyatt Williams (ODF) and Sarah Navarro (ODF).

Additional Notes

We appreciate any information regarding the accuracy or usefulness of the maps. If you have a chance to look at some of the mapped areas on the ground, please let us know what you observe. Please call Sarah Navarro (503-945-7394) or Danny Norlander (503-945-7395) if you have questions, suggestions, or comments.

The GIS data and a .pdf file can be accessed via the ODF web page at:

www.oregon.gov/ODF/ForestBenefits/Pages/ForestHealth.aspx

An online interactive ArcMap can be accessed via the Region 6 USFS web page at:

http://usfs.maps.arcgis.com/apps/MapJournal/index.html?appid=4dccf7c8314e43a78a93535b633d1632

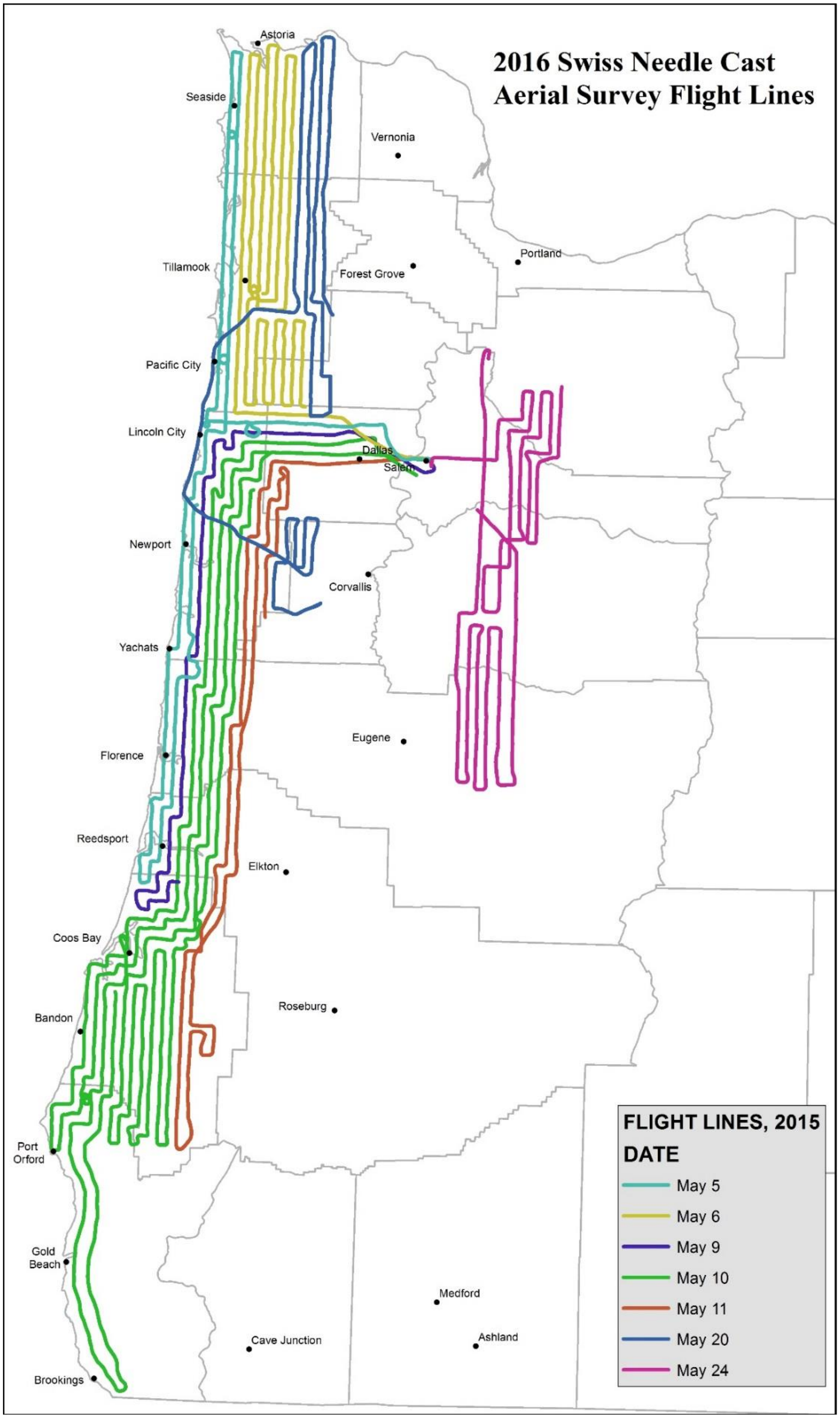


Figure 1. Area surveyed for Swiss needle cast symptoms, 2015. Flight lines are two miles apart.

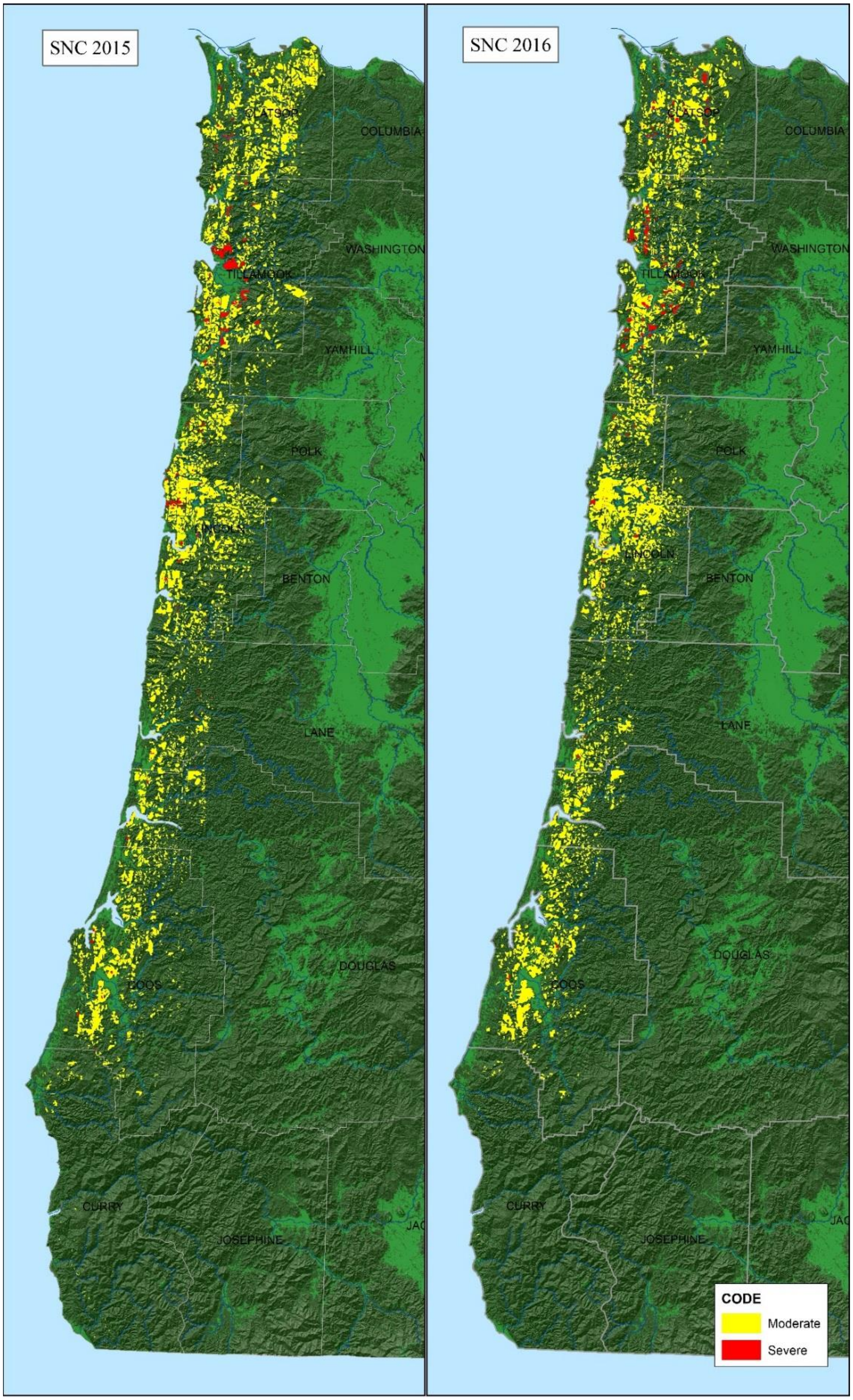


Figure 2. Areas of Douglas-fir forest with symptoms of Swiss Needle Cast detected in the 2014 and 2015 aerial surveys, Coast Range, Oregon.

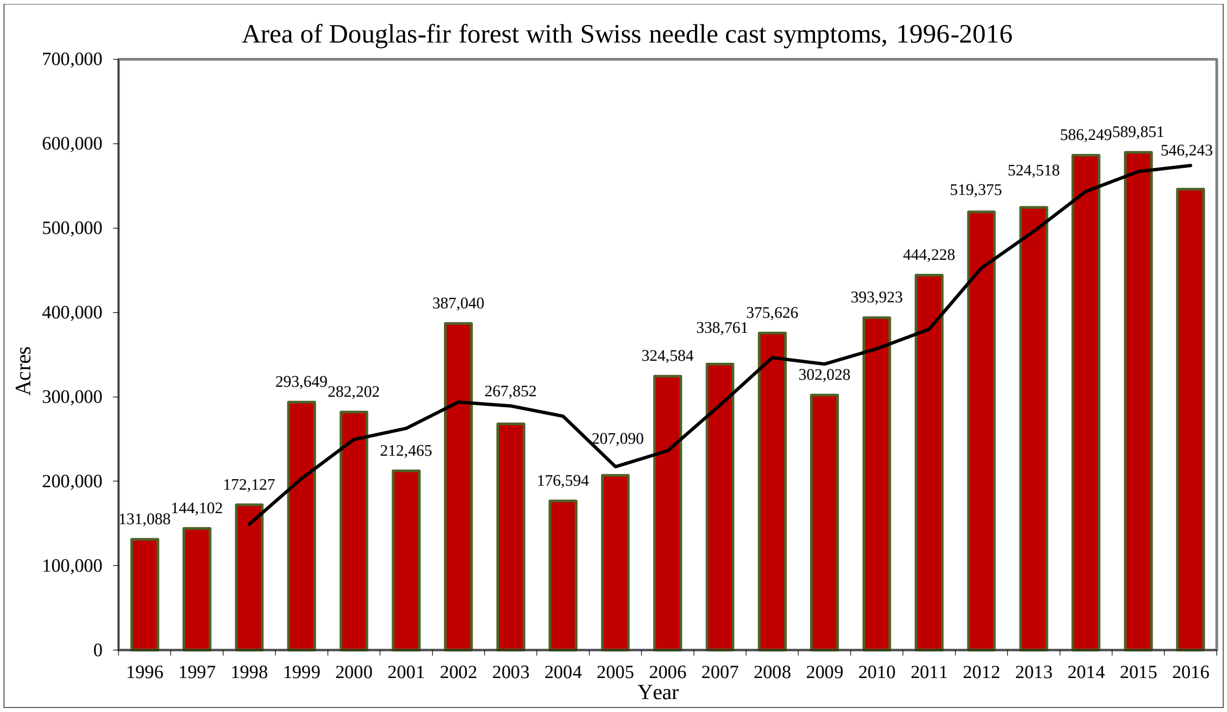


Figure 3. Area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys conducted in April-June, 1996-2016 (2008 area estimated from partial survey consisting of 3 sample blocks). Trend line is 3-year rolling average. Coast Range, Oregon

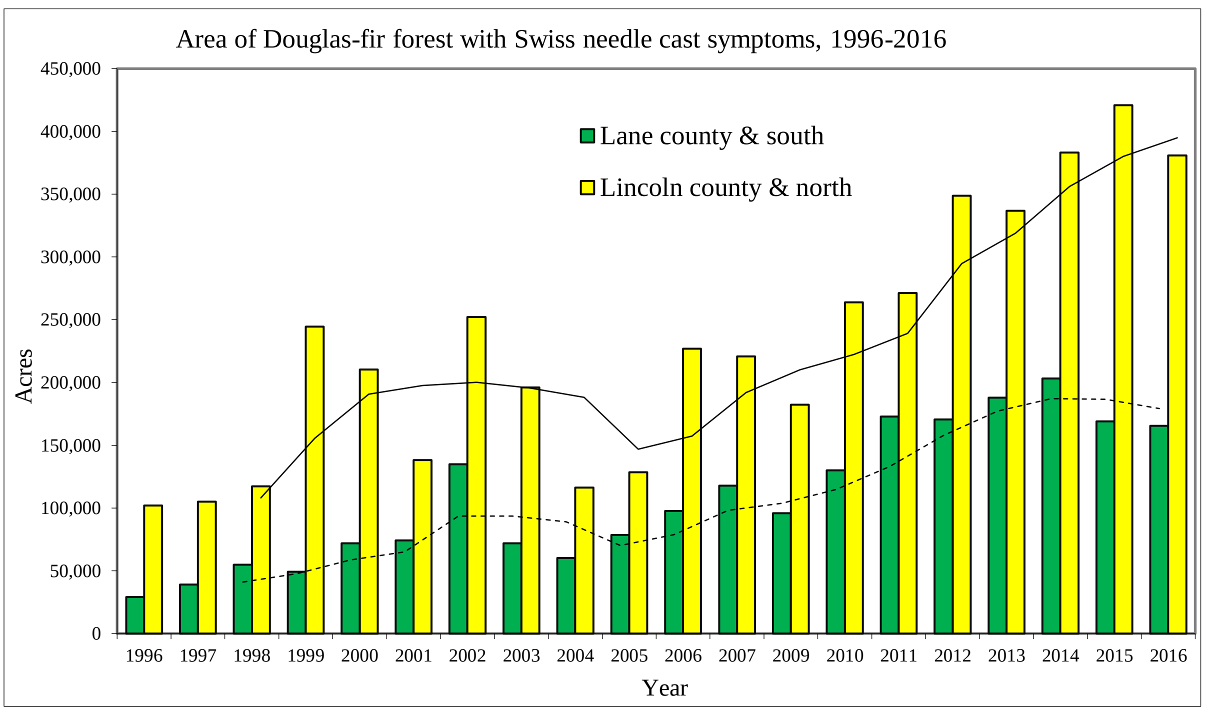


Figure 4. Area of Douglas-fir forest in western Oregon with symptoms of Swiss needle cast detected during aerial surveys conducted in April-June, 1996-2015; north and south halves of survey area (2008 area estimated from partial survey consisting of 3 sample blocks). Trend line is 3-year rolling average. Coast Range, Oregon.

Coastal Washington Swiss Needle Cast Aerial and Ground Survey, 2016

Amy Ramsey[1], Dan Omdal[1], Aleksandar Dozic[1], Glenn Kohler[1], Justin Hoff[2], Dylan Lynch[1]
[1]Washington Department of Natural Resources, Forest Health Program, Olympia, WA, [2]The

Abstract

In late April and May, an aerial survey, covering 2.4 million acres, was flown to detect and map the distribution of Swiss Needle Cast (SNC) symptoms in coastal Washington. Nearly 248,000 acres of symptomatic Douglas-fir were mapped, which is a 30% decrease from the 350,000 acres mapped in the 2015 aerial survey. Sixty-three ground sites across the range of the aerial survey were surveyed for SNC incidence and severity, determined by counting fungal reproductive structures in the stomata of Douglas-fir needles, and Douglas-fir needle retention. An average of 2.4 years of foliage were on the trees across all sites. The average percentage of occluded stomata on all sites was 1.6% for 2015 (1-year-old) foliage and 22.1% for 2014 foliage (2-years-old).

Introduction

The fungus that causes SNC, *Phaeocryptopus gaeumannii* (T.Rohde) Petrak is found throughout the range of its only host, Douglas-fir (Shaw et al. 2011). Swiss Needle Cast causes premature foliage loss and defoliation and can reduce growth of host trees, alter wood properties, and affect stand structure and development (Johnson et al. 2005, Maguire et al. 2011, Weiskittel et al. 2006). The disease is most damaging near the coast due to the fungi-favorable climatic (mild winters and wet springs and summers) and topographic conditions.

An aerial survey for SNC has been conducted in the Oregon Coast Range since 1996, with over 300,000 acres of SNC symptomatic Douglas-fir mapped since 2006 and over 400,000 acres mapped since 2011 (Kanaskie and Norlander 2014).

In 2016 a SNC aerial survey was coupled with a ground survey in Washington. Ground surveys have been conducted in Washington since 1997, with aerial surveys occurring in 1998-2000, 2012, 2015 and 2016. The objective of the ground surveys is to monitor changes in incidence and severity of the disease over time.

Methods

The aerial survey observation plane flew at 1,500 to 2,000 feet above the terrain, following north-south or east-west lines separated by 3 miles. Observers looked for areas of Douglas-fir forest with obvious yellow-brown foliage, a rather generic symptom that appears to be indicative of moderate to severe SNC disease. Patches of forest with these symptoms were sketched onto computer touch-screens displaying topographic maps or ortho-photos and the position of the aircraft. Each polygon was classified for degree of discoloration as either “S” (severe) or “M” (moderate). Polygons classified as “S” (CODE, SNC-S) had very sparse crowns and brownish foliage, while those classified as “M” (CODE, SNC-M) were predominantly yellow-brown foliage with slightly denser crowns than those classified as “S”.

The 2016 Washington SNC aerial survey was flown on April 18, 20 and May 2 and covered 2,431,000 acres of forest. The survey is timed to occur when the crown color symptoms have developed, but before the new foliage has emerged (bud break) in late spring. The survey area extended from the Columbia River in Washington north to the Strait of Juan de Fuca, and from the coastline eastward.

Sixty-three ground sites were included in the SNC survey. Stand color, landscape position, elevation, aspect and average tree age were recorded for each site. Foliar retention, diameter at breast height and crown color were recorded for ten trees at each site. Foliage from 2015 and 2014 were collected from the upper third of each of the ten trees at each site and taken back to the lab for microscopic examination of *P. gaeumannii* pseudothecia, a reproductive structure of the fungus. Three hundred stomata on each of ten needles from each foliage cohort were examined for pseudothecial occurrence.

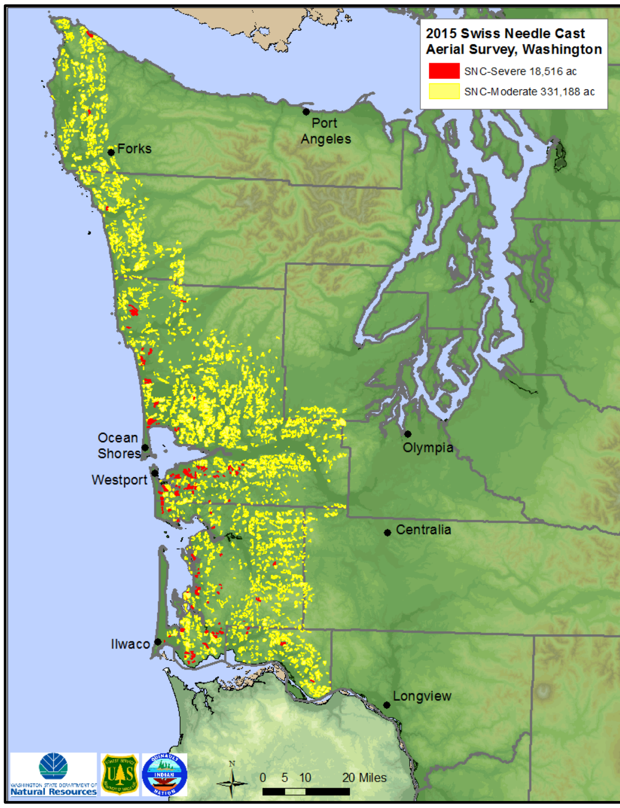
Results and discussion

The aerial surveyors flew and made observations on 2.4 million acres of forest land in coastal Washington and mapped 248,000 of Douglas-fir with obvious symptoms of SNC (Figure 1). This is a 30% decrease from the 350,000 acres mapped during the 2015 SNC aerial survey (Figure 2, Table 1). The survey boundaries were similar to those in the 2012 and 2015 surveys. The easternmost area with obvious SNC symptoms was approximately 45 miles inland in central coastal western Washington.

	Severe SNC Symptoms		Moderate SNC Symptoms		Total Acres Mapped	
Year of Survey	% of total acres mapped	Severe SNC Acres	% of total acres mapped	Moderate SNC Acres	% with SNC symptoms	Total SNC Acres
2016	> 1%	14,000	10%	234,000	10%	248,000
2015	1%	19,000	13%	332,000	14%	351,000
2012	> 1%	6,000	8%	222,000	9%	228,000

Table 1. Total acres with Swiss Needle Cast symptoms mapped during the aerial survey, by year.

Swiss Needle Cast symptoms were detected on 10% of the total acres surveyed, with 0.5% of the total area surveyed mapped as severe and 10% mapped as moderate (Table 1). Severely symptomatic stands were generally located near the Grays Harbor area, which is near Ocean Shores and Westport, and the most southwest corner of the survey, near Ilwaco. The cause of the decrease in mapped acres from 2015 to 2016 remains uncertain, but it is likely a combination of environmental factors influencing infections patterns and foliar retention and variations in aerially observed symptom signatures. Figure 3 shows how the 2016 SNC aerial survey compares to previous years SNC aerial surveys in Washington.



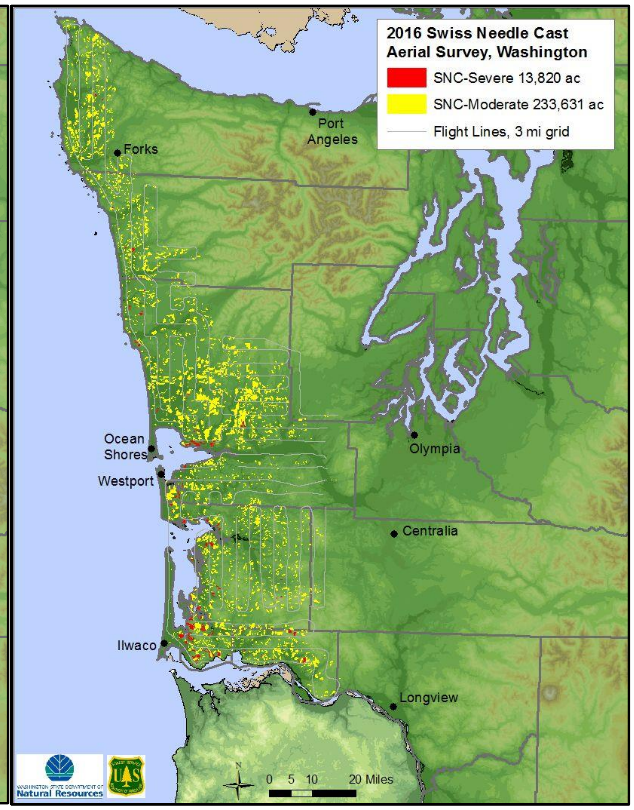


Figure 1 (right). Washington 2016 Swiss needle cast (SNC) aerial survey map. 248,000 acres of affected area mapped. **Figure 2** (left). Washington 2015 Swiss needle cast aerial survey map. 350,000 acres of affected area mapped.

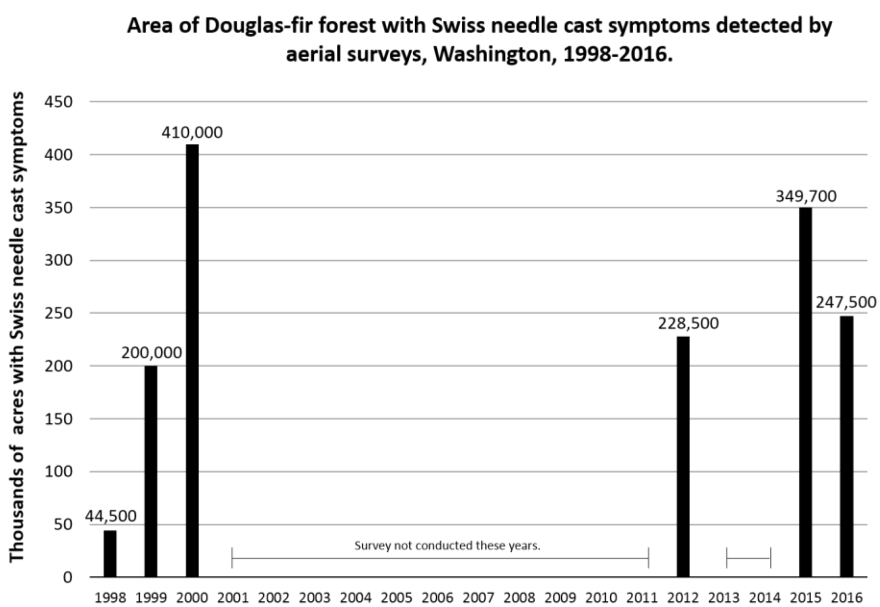


Figure 3. Area of Douglas-fir forest with Swiss needle cast symptoms detected by aerial surveys in Washington, 1998-2016.

Foliar retention varied across the survey area, ranging from 1.7 to 3.7 years, with an average of 2.4 years across all sixty-three ground survey sites. The average percentage of occluded stomata across all sites was 1.6% for 2015 (1-year-old) foliage and 22.1% for 2014 foliage (2-years-old), with ranges from 0 to 72 percent, depending on the tree, site and needle age. There were no significant differences in foliar retention values and two-year old needle pseudothecia occlusion percentages among the 2011, 2012, 2015 and 2016 ground survey data.

Caution should be advised when interpreting aerial survey data. The SNC survey should be considered a conservative estimate of the acreage affected by SNC because aerial observers can only map areas where disease symptoms have developed enough to be visible from the air. SNC aerial survey can be used to coarsely document trends in damage over time. The ground data indicates that SNC is present in areas that were not mapped during the aerial survey. While the aerial survey can be used as a guide for identifying areas impacted by SNC, on the ground surveys should be conducted in stands of interest before SNC mitigating management decisions are made.

Douglas-fir is the only host of this disease, therefore forest managers can grow non-host species such as red alder, western red cedar, western hemlock and Sitka spruce in efforts to reduce damage from SNC. However, it should be noted that if Douglas-fir has more than three years of foliage on its branches, then damage in the form of growth loss are likely to be minimal to none.

For more information about foliar retention assessments or Swiss Needle Cast in general, this document has some great information. http://sncc.forestry.oregonstate.edu/sites/default/files/ForestHealthFS.pdf.

For more information and details about the SNC aerial survey, follow this link to a storyboard about the survey. http://usfs.maps.arcgis.com/apps/MapJournal/index.html?appid=4dccf7c8314e43a78a93535b633d1632

Acknowledgements

The survey was conducted by the Washington Department of Natural Resources (WDNR) Forest Health Program and the Washington Department of Fish and Wildlife (WDFW) aviation section. Marty Kimbrel (WDFW) piloted the plane. Funding for the survey was provided by the Washington State Legislature, Washington Department of Natural Resources and the USDA Forest Service, an equal opportunity employer.

Additional Notes

We appreciate any information regarding the accuracy or usefulness of the maps and ground survey data. Please contact Amy Ramsey (amy.ramsey@dnr.wa.gov or 360-902-1309) if you have questions, comments or suggestions.

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Detecting Swiss Needle Cast in Coastal Douglas-fir using a Low-cost Unmanned Aerial System equipped with a Consumer-grade Digital Camera

Jonathan Burnett
Department of Forest Engineering, Resources, and Management, Oregon State University

Introduction

Swiss needle cast (SNC) is a foliar disease in Douglas-fir caused by the native fungus *Phaeocryptopus gaeumannii* (Hansen et al. 2000). SNC has been intensifying in Oregon's Coast Range in the 1980's (Black 2010). The disease is of special concern to the region and the state of Oregon because Douglas-fir (*Pseudotsuga menziesii)* is the major lumber producing species (Brandt 2006), contributing to the State's $12.7 billion annual industrial forest output (OFRI 2013). SNC causes premature leaf abscission, which reduces annual growth increment that can accumulate to end-of-rotation volume losses as high as 50% (Manter et al. 2000; Maguire 2002). These projected volume losses lead to significant reductions in stand net present value (Kimberley et al. 2011). Accurate maps of SNC infection in Douglas-fir stands are critical for employing mitigation strategies such as stand conversion or thinning treatments that favor non-susceptible tree species such as hemlock or western redcedar (Shaw et al. 2011; Zhao et al. 2015).

The conventional method of mapping SNC is aerial detection survey (ADS), which uses trained observers in an aircraft who map disease severity (MacLean et al. 1996; Kanaskie et al. 2007; Johnson and Dwittwer 2008). Major advantage to ADS is an immediate application of expert knowledge across a broad area and the survey results require minimal post-processing to create actionable maps of disease extent and severity. However, ADS is not without limitation. Enough trees must be affected by SNC for the observer to detect presence from thousands of feet above the ground while moving at a speed of 100+ mph. Also, the spatial accuracy of results is at the acre level and not sufficient for individual tree assessments that are better suited for stand-level decision making. The spring phenology of the disease signature aligns with Oregon's rainy season, which can limit manned flights and create poor canopy illumination for SNC detection. The use of Unmanned Aircraft Systems (UAS) offers a potential solution to these limitations by removing humans from the aircraft, conducting near canopy observations (~ 400' above ground) and employing conventional quantitative remote sensing techniques for analyzing images.

A UAS equipped with a digital camera and flying lower than 400' above ground level (AGL) can produce images with approximately 1" ground sampling distance (GSD) (Wing et al. 2013). The images can be used individually for conventional photo interpretation and if there are enough overlapping images they can be compiled into a single georeferenced orthomosaic and digital surface model using structure from motion (SFM) (Verhoeven 2011; Gross 2015). Orthomosaics, especially when produced from linear sensors calibrated to surface reflectance, can be used in conventional remote sensing workflows that look for quantitative patterns in the data to classify pixels such as maximum likelihood classification, logistic regression and advanced computer learning algorithms such as Random Forest (Laliberte and Rango 2009; Lillesand and Kiefer 2008; Liaw and Wiener 2002).

This study examined the accuracy of detecting SNC presence in Oregon coast Douglas-fir trees with a novel UAS remote sensing technique. We evaluated the accuracy of SNC detection using UAS, compared accuracy of detection between consumer-grade and commercial-grade cameras and examined trends in disease presence and detection sensitivity within stands across two years and between spring and summer.

Methods

Four study sites were selected from sites within the Swiss Needle Cast Cooperative's plot network (Ritóková et al. SNCC 2014) in western Oregon and divided into 10 approximately 5 to 10 acre areas. Criteria for stand selection was based on prior knowledge of SNC presence, coverage from an existing Federal Aviation Administration Certificate of Authorization (COA) and the ability to maintain line of sight to an unmanned aircraft flying 400' above ground level (AGL). Sites ranged from 5 to 20 acres in size with Douglas-fir cohorts ranging between 25 and 60 years of age and terrain relief of 0 to 250 feet. The survey was conducted in May 2015, May 2016 and August 2016. May flight timing corresponded with the phenological response of Douglas-fir to SNC infection (Manter et al. 2000) and the timing of the statewide ADS.

Various quadcopter UASs were used over the course of this study to lift a Sony A5100 24 megapixel consumer-grade camera and a MicaSense RedEdge commercial-grade multispectral camera. The systems cost was about $7500, including the $5500 MS sensor. The 10 areas were flown with the UAS along preprogrammed flight lines that ensured ~80% overlap and 80% sidelap of all images. Images were mosaicked using Agisoft Photoscan ver. 2.1. This produced a color orthomosaic at 2 cm resolution and a digital surface model (DSM) at 5 cm for each of the areas. Tree populations for each site were automatically extracted from the DSM using FUSION CanopyMaxima. Color information from the orthomosaic was averaged over the crown area of each of the trees at each area to produce tree level color reflectance metrics. Three hundred training trees were randomly selected from the tree population at each area. Trees were classified as 'diseased' or 'undiseased' by visual interpretation with the assistance of a forest insect and disease detection expert.

A Random Forest classification model (Liaw and Weiner 2002) was created using the 300 training trees. The model ascertains a disease status as a function of the color reflectance of the tree. Model accuracy was assessed using a balanced accuracy metric, which accounts for imbalances in the number of diseased/undiseased trees in the training data and a kappa statistic, the latter which is commonly used in remote sensing. Model strength was assessed using the 'receiver operating curve'. Confidence intervals on these two metrics were produced using a k-fold cross-validation routine to resample the training data and refit Random Forest models.

These three metrics were compared among areas, between sensors, between seasons and between years to evaluate stability of the model. The best performing model and sensor combination was then used to classify the entire tree population in each area to make inference about SNC severity among areas, between seasons and between years.

Preliminary Results and Conclusions

Analysis of results is still ongoing. Preliminary results suggest that the commercial-grade sensor performs significantly better than the consumer grade camera and that model accuracy is better in May than in August. The geographically explicit tree-level disease detection maps are immediately interpretable (Figure 1) and will be useful for directly supporting thinning prescriptions and cost-benefit analysis of species conversion. Regardless of the results, the complexity of using small UAS to perform this type of survey makes it cost prohibitive relative to the conventional ADS. The economy of scale simply is not there. However, if the classification model is determined to be generalizable across the study sites, this study may set the stage for further research that will eventually lead to an automated wide area survey for SNC. Once automatic detection routines can be combined with large UASs capable of long endurance (3+ hours) and beyond line of site flights, there is a real potential for supplementing or even replacing conventional aerial survey methods.

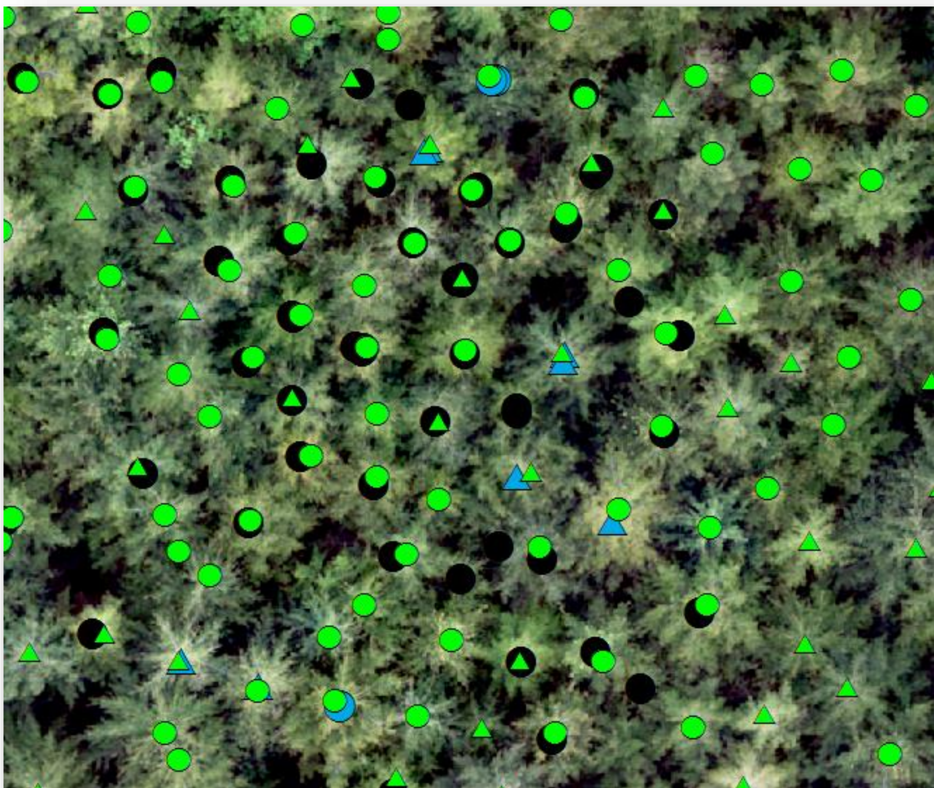

Figure 1 - Disease detection over an SNCC Research Plot: Comparison of SNC foliage retention (FR) to disease detection status. Blue triangle = FR < 2.5 yrs, Blue circle = FR >= 2.5 yrs, Black circle = not rated, Green circle = Not Diseased, Green triangle = Diseased. Detection model detected disease on 4/5 trees with FR < 2.5.

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Swiss Needle Cast Cooperative Research and Monitoring Plot Network

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Introduction

Among the long term objectives of the SNCC is a constant monitoring of disease conditions. While this can be accomplished qualitatively with the results of the annual aerial survey, quantitative assessment of the tree growth loss resulting from Swiss needle cast requires periodic measurements. This has been accomplished up until now with the Growth Impact Study (GIS) plot network (Maguire et al. 2011).

During the final remeasurement of the GIS plots (2008), it was decided that their utility had become limited. The original sample of 10-30 year old GIS stands is now 25-45, which is considered outside the age range of those stands for which information is especially valuable. Furthermore, ground observation of foliage retention, the original methodology for determining disease severity, has become difficult to impossible as a result of crown recession and canopy closure. In addition, these plots were distributed only between Newport and Astoria, thereby providing inference only to the northern Oregon Coast Range.

In order to address these limitations, the decision was made to install a new monitoring plot network, which is foreseen to provide disease condition and growth loss information for at least 10 years. These plots have been installed in 10-20 year stands, thereby addressing the shortcomings of the aged GIS network. In addition, these plots will be distributed as far south as the California border, and as far north as southern Washington.

These plots will not only provide periodic information about disease severity, growth loss and its geographic distribution, but will also offer sites to be used for other SNC research, be it epidemiological, climatological, or other forms.

Methods

Criteria for selection

Candidate stands should not be treated by fertilization or disturbed (thinned, cleared) for ten years. The selected one-fifth acre plots with a 0.5 chain buffer (0.58 ac) should have not been pre-commercially thinned or fertilized in the past 5 years. The targeted basal area composition is 80% Douglas-fir, targeted age between 10 and 30-years old of Douglas-fir. Ideally dense understory should be avoided and density aimed to 300-400 trees per acre.

At each plot, a 1/5 acre plot has been laid out, and all trees tagged. Field methods have followed Kanaskie and Maguire, March 30, 2002 Field Specifications and Manual for Rating

Swiss Needle Cast in Douglas-fir. The following is adapted from that document but specific to the 1/5 acre plot and needle retention will be estimated in years.

Sampling matrix

We identified four zones based on distance from coast (in miles): 0-5, 5-15, 15-25, and 25-35. Each of these zones was equally divided (north-south), following township lines as closely as possible. Each block spans approximately 58 miles north-south. This resulted in 20 sampling blocks. In addition to the 20 cell matrix in coastal Oregon, 4 sampling blocks were established in SW Washington. Attached Google Earth image shows these blocks (Figure 1.)

Sites

In the three year installation period, we established 106 research plots, of which 98 are located in Oregon and 8 are in SW Washington on DNR property (Figure 1.)

Measurements

Following the establishment and marking of plot boundaries, all trees were given a unique numbered tag. Following the conclusion of growing seasons, all trees were measured for dbh and species was recorded. A forty tree height sample was collected, such that it included the 10 largest trees by dbh, the four smallest by dbh, and the final 26 were ranged across the diameter distribution. In the spring of 2014 and 2015, the 10 largest trees were climbed, foliage collected from upper, middle and lower crown for pseudothecial occlusion, foliage retention assessment and foliar nutrition. In addition, soil samples were collected for Jeff Hatten's soil study.

Figure 1. Research plot network matrix and research plots distributed throughout the matrix. Colored pins represent plot establishment years. White – 2013, blue – 2014, pink – 2015.

Currently we are processing needles from branches collected in spring 2016, assessing incidence on one- and two-year old needles, and pseudothecial occlusion on two-year-old needles only. The laboratory component of the project will be completed at the end of March, from which point we will analyze the collected data.

Acknowledgements

We would like to express our appreciation for collaborative efforts from numerous landowners, who gave us permission to establish research plots on their lands and at times provided assistance in the field. Besides the SNCC members (Oregon Department of Forestry, Bureau of Land Management, USDA Forest Service, Starker Forests, Stimson Lumber, Weyerhaeuser), we are grateful to Lewis & Clark Tree Farms, Greenwood Resources (formerly Campbell Group), Washington DNR, Hampton Affiliates, Hancock Forest Management, Roseburg Resources, South Coast Lumber,

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The Effect of Swiss Needle Cast on Stem Taper of Douglas-fir from 26-40 yr-old Plantations in North Coastal Oregon

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Abstract

A taper equation was fit to data collected from Swiss needle cast (SNC) infected Douglas-fir trees over the period between 1998 and 2015 to assess to assess the effect on the stem form. Based on stem analysis of 88 trees from both healthy and infected stands aged between 26 and 40 in 2015, sustained SNC infection has been found to lead to increasing differences in upper stem diameter over time. Based on average dataset tree sizes in each growth period, a tree with a foliage retention (FR) of 1.5 years was implied to have a 0.3, 0.9, 0.7, 1.1, and 2.1 cm smaller diameter inside bark (DIB) at 40% of total tree height than the same sized healthy tree (FR=3.5 yrs) in 2000, 2002, 2004, 2008, and 2015 respectively. Based on the average tree size in 2015 (dbh=35.4 cm, ht=26.8 m), a tree from an infected stand (FR=1.5 yrs) is implied to have 10% less cubic volume and 22% less Scribner volume than a tree from a healthy stand, a difference which is not accounted for using volume equations that depend only on height and diameter.

Introduction

Since the mid to late 1980s, Douglas-fir growing in the Oregon Coast Range have been affected by the endemic foliar fungus *Phaeocryptopus gaeumannii*, the cause of the Swiss needle cast (SNC) epidemic that has resulted in significant defoliation and subsequent volume growth losses (Maguire et al. 2011). While a healthy Douglas-fir in western Oregon forests generally retains 3-6 years of needle cohorts, infected trees may retain as few as a single cohort (Hansen et al. 2000, Maguire et al. 2002). Furthermore, defoliation tends to be focused in the upper crown, perhaps due both to enhanced fungal spore deposition, germination, and development, as well as greater physical forces causing defoliation (Hansen et al. 2000). In contrast, trees in stands suffering significant foliar losses often retain significant foliar mass in lower crowns. Previous research has shown that while overall foliar mass of infected trees decreased significantly, a larger proportion of foliar mass of a given age was carried lower in the crown (Weiskittel et al. 2006).

The change in vertical foliage distribution due to SNC can be expected to influence the stem form of infected trees. It has long been known that the distribution of diameter increment throughout the height of a tree is strongly dependent upon crown size and condition (Forward and Nolan 1961, Larson 1963, Fajvan et al. 2008, Goudiaby et al. 2012). The accuracy of taper equations in Douglas-fir has therefore been improved by including crown ratio as a predictor variable (Walters and Hann 1986). Previous research assessing the applicability of existing taper equations for predicting stem diameter increment and taper of SNC-impacted trees (Weiskittel and Maguire 2004) indicated that the greater the intensity of SNC (lower the foliage retention), the stem for a given dbh, height, and live crown length is more narrow. This result agrees with numerous studies that have established that the cross-sectional increment at any given height on the stem is proportional to the amount of foliage above that height (Larson 1963).

The dataset used for the Weiskittel and Maguire (2004) analysis included 105 trees from age 11 to 62, and thus much of the stem within the older trees grew before the onset of the current SNC epidemic. More recent observations in Swiss needle cast infected stands suggest that stem form may be even more heavily impacted due to cumulative effects of SNC since the 2004 study. Trees that have been subjected to the disease for an additional 10 years are likely to have more pronounced changes in stem form imposed by SNC.

Production of a new taper equation that accounts for the effects of SNC would help evaluate growth impacts of SNC and facilitate more accurate harvest volumes and log dimensions. Early and viable commercial entries into young stands depend on the availability of sawlogs, and this requires predicting the volume of wood that meets a minimum scaling diameter to make the entry profitable. In addition, previous analyses aiming to assess the volume growth impact of SNC have estimated volumes of measured trees using an existing volume equation that account for dbh and height only (Mainwaring et al. 2005, Maguire et al. 2011). In not accounting for potential differences in stem form between healthy and infected trees, published volume growth losses may be underestimated.

Fortunately, retirement of the SNCC growth impact plots (Maguire et al. 2011) provides a source of numerous stands that have reached ages typical of those that are thinned or clearcut, and that have had a 17-year history of tree measurements and SNC ratings. Stem analysis of sample trees from these plots would significantly enhance an assessment of SNC impacts on stem form. The objectives of this report are to: 1) develop a stem taper equation that accounts for the intensity of SNC on various taper function parameters; and 2) test the hypothesis that the effect of SNC on stem form has intensified during the 17 years over which these permanent plots have been measured.

Methods

Field

Study plots were established in the spring of 1998, in stands randomly chosen from among a compiled list of all 10-30-year-old plantations in the northern Oregon Coast Range (Maguire et al. 2011). The 76 plots were distributed from 44.6 to 46.2 north latitude and from -124.0 to -123.2 west longitude, and from 23 to 622 m above sea level. Over the last 40 years in this region, the mean January minimum was 0°C and the mean July maximum was 25°C. Total annual precipitation averaged 150-300 cm, with approximately 70% of the total falling between October and March. Plots were measured at the time of establishment, and again in the spring of 2000, 2002, 2004, and 2008. Measurements included dbh and height and height to crown base on a subsample of 40 Douglas-fir per plot. Measurements included estimates of foliage retention on the same 10 trees each period (SNC rating trees) in the spring just prior to budburst.

For the purposes of the taper study, eighteen of the remaining intact plots were systematically chosen for taper sampling, distributed as uniformly as possible across the range of foliage retentions (FR), stand age, and stand density as estimated in 2008 (figure 1). The sample included the four plots with the greatest FR in 2008, the four with the lowest FR, and 10 plots distributed across the FR distribution. Figure 2 indicates that the tree sample provided a well-distributed range in diameter, height, and foliage retention.

In each stand, five undamaged and unforked trees were selected for stem form analysis. This sample included the two largest trees that had served as SNC rating trees, a tree with dbh corresponding to Douglas-fir quadratic mean diameter (QMD) for the plot, and two other trees with dbh between QMD and maximum dbh for the plot.

Figure 1. Locations of the 18 study plots from which trees were sampled.

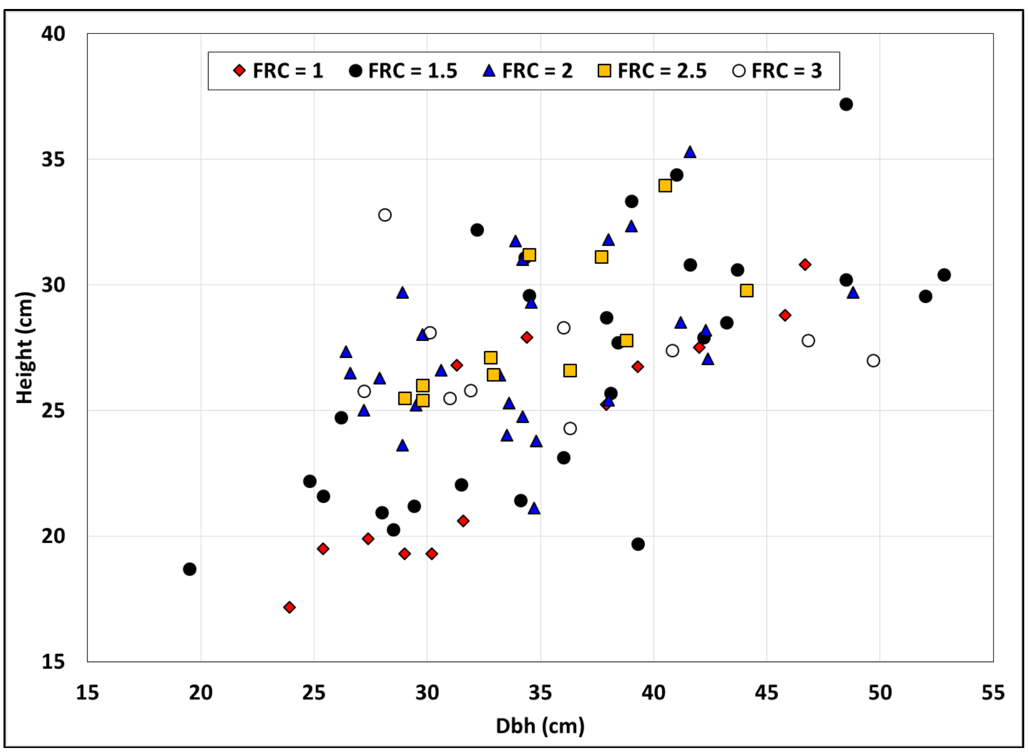

Figure 2. Diameters and heights of the sample trees in 2015. Trees are color coded by foliage retention class.

Whenever possible, trees were selected from among trees previously rated for FR. Sampled trees were also selected from among the trees previously measured for the 40 tree height subsample to ensure that previous measurements of height to crown base was available on all sampled trees.

Diameter of the tree was measured with a dbh tape before cutting (nearest 0.1 cm). Each sample tree was felled leaving a sufficiently tall stump so that a disk could be cut at a 15-cm height from ground level. The following heights were measured on each felled tree to the nearest 0.01m: total height, height to lowest live branch, and heights corresponding to the year of each previous tree measurements (8, 12, 14, 16 and 18 years previous).

On all trees, a stump disk was cut at 15 cm above ground level on the uphill side of the tree, and a breast height disk was cut at exactly 1.37 m., it will be important to measure the exact height of tag attachment (i.e., the height at which all previous dbhs were measured). All remaining disks above breast height were sampled at approximately the midpoint between two adjacent whorls, allowing for shifts up or down to avoid stem defects or relatively large interwhorl branches. Disks above breast height were taken from approximately every other whorl, with a total target count of 15-20 disks per tree.

Before cutting each disk, the diameter outside bark (dob) to the nearest 0.1 cm was measured with a diameter tape and the height to the top of the disk will be measured to the nearest 0.01m. Disks were cut such that the top of the disk was at the height of the mark. Each disk should be labelled on the bottom side of the disk for Plot #, tree #, and disk #). Cut disks were stored in a cooler until they were measured in the lab.

In the upper stem with dob<10 cm, disks were cut every whorl until the stem dob<5cm.

Lab

Disks were measured on the top side. One line was drawn through the pith across the longest axis. A second line was drawn 90° to the first and through the pith. The following values were recorded for each axis: 1) Total diameter outside bark (dob); 2) total diameter inside bark (dib); 3) total heartwood width; and 4) number of growth rings on both sides of the sapwood.

On each of the two marked axes, the diameter inside bark (dib) was measured that corresponds to the spring dbh measurements in 2008, 2004, 2002, 2000, and 1998 (8, 12, 14, 16 and 18 years back).

Analysis

A total of 87 trees were subjected to stem analysis. The chosen model form was the variable exponent form (Kozak 1988). The variable exponent form models the ratio of diameter inside bark (DIB) at height *h* to DIB at breast height:

[1] dib/DIB=X^c

where $X=(1-Z^{0.5})/(1-p^{0.5})$

$Z= h/HT$

p=height where tree shape changes from neoloid to paraboloid form (=0.5 m)

C=a function of Z and other tree variables

The choice of the final model form, shown below, was based on both the minimization of bias at different levels of foliage retention, and its suitability for predicting stem form in separate growth periods:

[2] dib/DIB=$X^{(b1*Z^2+b2*Z^0.5+b3*exp(Z)+b4*dbh +b5*LCR+b6*FR+b7*FR*Z)}$

where

dbh = diameter at breast height of subject tree at start of period (cm)

LCR = natural log of crown ratio of subject tree at start of period

FR = Foliage retention of subject tree at start of period (yrs)

The taper equation was used to estimate volumes by numerical integration of trees by segment from the 0.15 m stump to total tree height. The average cross sectional area for the top and bottom of each segment were used with Smalian's formula to estimate segment volumes.

Results

Equation [2] was chosen for the final model due to low bias, particularly at different levels of SNC. Equation [2] provided a significant fit for the final four of the six growth periods, with parameter estimates provided in table 2. Table 2 also provides fits for the 1998 and 2000 measurements, based on reduced versions of equation [2].

SNC did not demonstrate a significant effect on stem form in 1998. Starting with measurements made of the sampled trees in 2000, SNC exhibited a negative effect on predicted upper stem dib (figure 3), with this effect generally increasing over time (figure 4). This negative effect was most obvious in the lower part of the tree, with the largest difference between healthy and infected trees apparent at between 30-40% of total tree height (figure 4). Equation [2] also predicts that infected trees have a larger dib at a given relative height in the upper stem (figures 3, 4). The relative height above which this is apparent has shifted upward, from the top 42% of the tree in 2000, to the top 13% in 2015.

Maximum differences in upper stem diameter between healthy trees (FR=3.5 yrs) and infected trees (FR=1.5 yrs) depended on tree size. Based on an average tree size of 35 cm dbh and 27 m in 2015, equation [2] predicted a maximum difference of 0.3 cm in 2000, 0.9 cm in 2002, 0.7 cm in 2004, 1.1 cm in 2008, and 2.1 cm in 2015.

Applying this taper equation to predict cubic volumes, trees in 2000, 2002, 2004, 2008, and 2015 with a foliage retention of 1.5 years had 0.1, 4.5, 3.6, 6.1, and 10.1% less cubic volume than trees with a foliage retention 3.5 years, all else being equal.

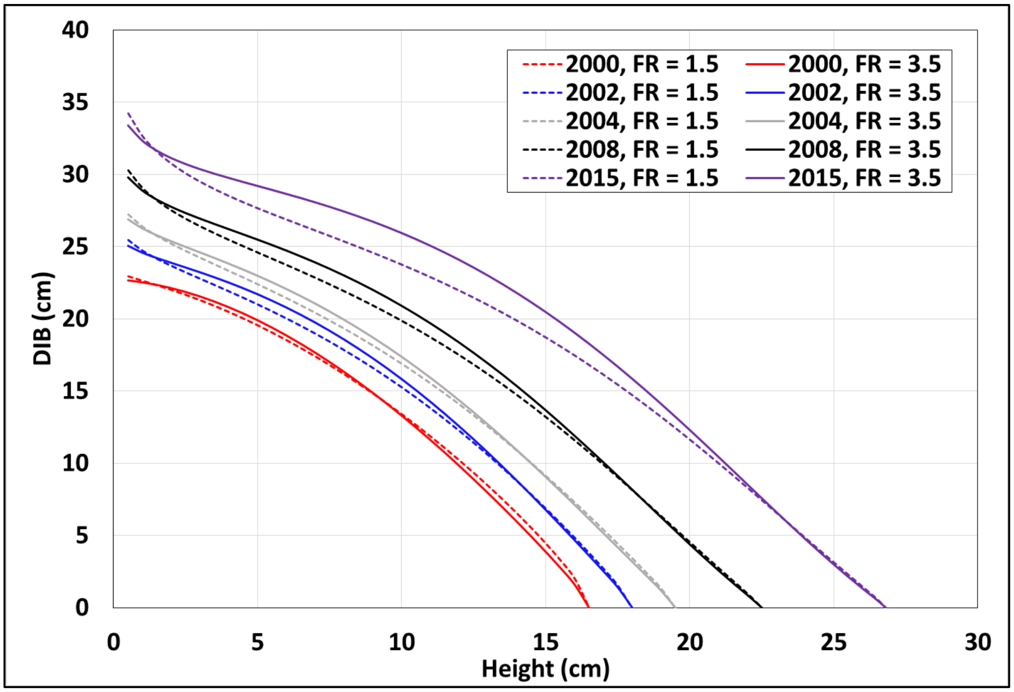

Figure 3. Implied upper stem dib and height from model fits shown in table 2, based on foliage retention of 3.5 yrs and 1.5 yrs, and average tree dimensions at the start in each growth period.

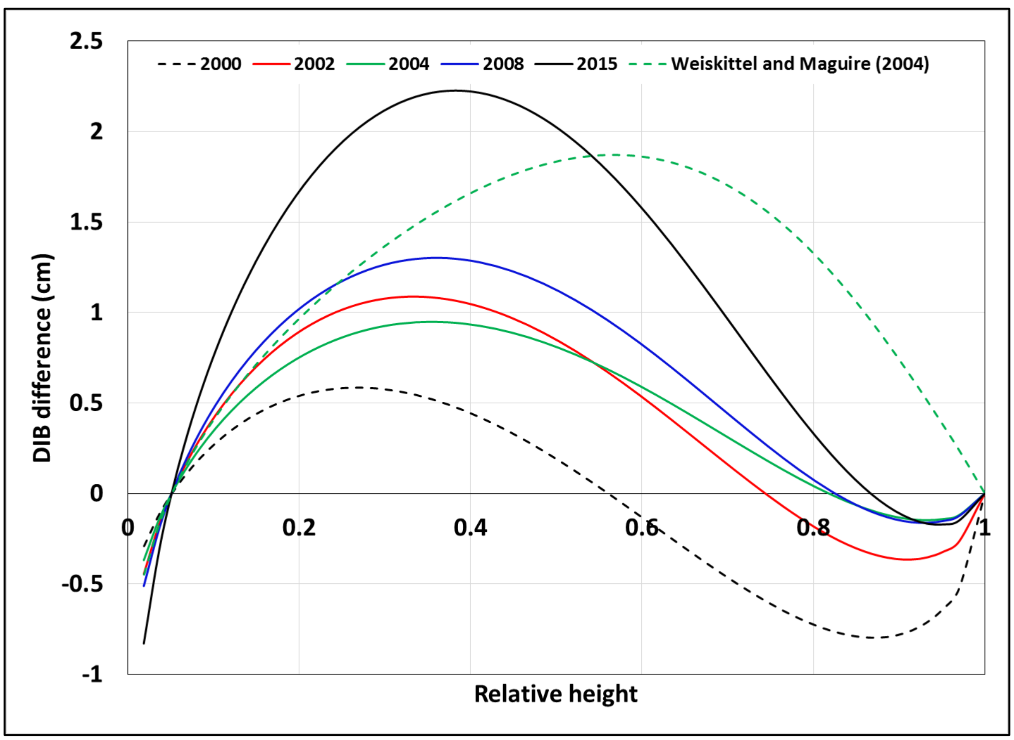

Figure 4. Implied difference in upper stem dib by year for healthy (FR=3.5 yrs) and infected (FR=1.5 yrs) trees, based on average tree size in 2015 (dbh=35.4 cm, ht=26.8 m).

Discussion

Differences in taper due to SNC, estimated by equation [2], are less than those estimated from previous work. For the same sized tree, the maximum difference in upper stem diameter as estimated by Weiskittel and Maguire (2004) was both larger (1.8 cm vs. 0.7 cm), and higher on the stem (55 vs. 35% of tree height). Based on sampling performed during the spring of 2002 and the winter of 2004, the earlier dataset spanned a larger range in size, varying from 13-67 cm in dbh and 12-46 m in height (Weiskittel and Maguire 2004). Whether the focus of the current study's dataset on merchantable trees in the upper half of a stand's diameter distribution contributes to this differences is unknown. Nevertheless, the current dataset is an appropriate sample for harvest-aged coastal stands managed for timber production. Furthermore, the focus on more dominant trees provides the best means of estimating upper stem diameters for those trees providing the majority of stand volume.

The relative decrease in upper stem diameter of infected trees over time was expected due to the effect of SNC on the distribution of foliage mass in the crown (Hansen 2000). It is expected that this trend will continue for as long as SNC is present in these stands.

The exception to this trend was the implied decrease in SNC-related taper in 2004 relative to that implied in 2002 (figure 4). While this difference was small, it provides further evidence of the influence of foliage retention. For the purposes of developing climate-based SNC prediction models, analyses have been conducted to predict foliage retention from any of a number of measured or estimated climate variables (Manter et al. 2005, Zhao et al. 2011). These studies have determined that foliage retention, as an index of SNC severity, is negatively correlated with spring moisture and winter temperature. Spring moisture is important for fungal germination because only current year foliage can become infected, and only during the period of shoot elongation (Stone et al. 2000). In 2002 and 2003, precipitation measured at five weather stations throughout the study area (Nehalem, Otis Junction, Seaside, Tillamook, Willamina) was at its lowest level in the previous 10 years (fig. 5). Tracking this was a decrease in acreage reported as showing SNC symptoms by Oregon Department of Forestry's (ODF) aerial survey in 2003 and 2004 (Kanaskie et al. 2006), suggesting a one-year delay in symptom expression. This delay is consistent with the spring moisture hypothesis, given that symptom expression takes place in older needle cohorts about to be cast, thereby requiring at least one season of post-germination fungal development. Consistent with the results of the ODF aerial survey, during annual ground foliage surveys in 2006 and 2007 many trees were observed to have a greater amount of 2003 foliage than 2004 foliage (personal observation). Thus, improved foliage retention following the relatively dry springs in 2002 and 2003 may explain the small improvement in taper in 2004 relative to 2002.

Previous analyses looking at the effect of SNC on productivity have generally used existing volume equations, applied to tree lists at the start and end of growth periods to determine volume growth (Mainwaring et al. 2005, Maguire et al. 2011). Given that upper stem diameter for a given DBH are smaller for an infected tree, this method of estimating tree volume can be expected to overestimate volume growth over a period, and particularly over long periods. Of greater concern are one time volume estimates from cruises or inventories that fail to account for SNC-related differences in stem form. While it is estimated that cubic volume for an infected tree is 10% lower than that of a healthy tree, all else being equal, this difference is likely to be greater if volume is measured in Scribner board feet. According to the Scribner Rule, log volumes are based on truncated upper stem diameters measured by the inch. Because the 2015 upper stem DIB of the averaged size tree of an infected stand (FR=1.5 yr) was estimated to be nearly one inch smaller than that of a healthy tree given similar DBH and height, the implied Scribner volume of a 40 foot log from the infected tree (assuming scaling DIB of 6, 7, 8, 9, or 10 inches for the healthy tree) would be 33, 14, 22, 25, or 20% lower (Northwest Log Rules Advisory Group 2003).

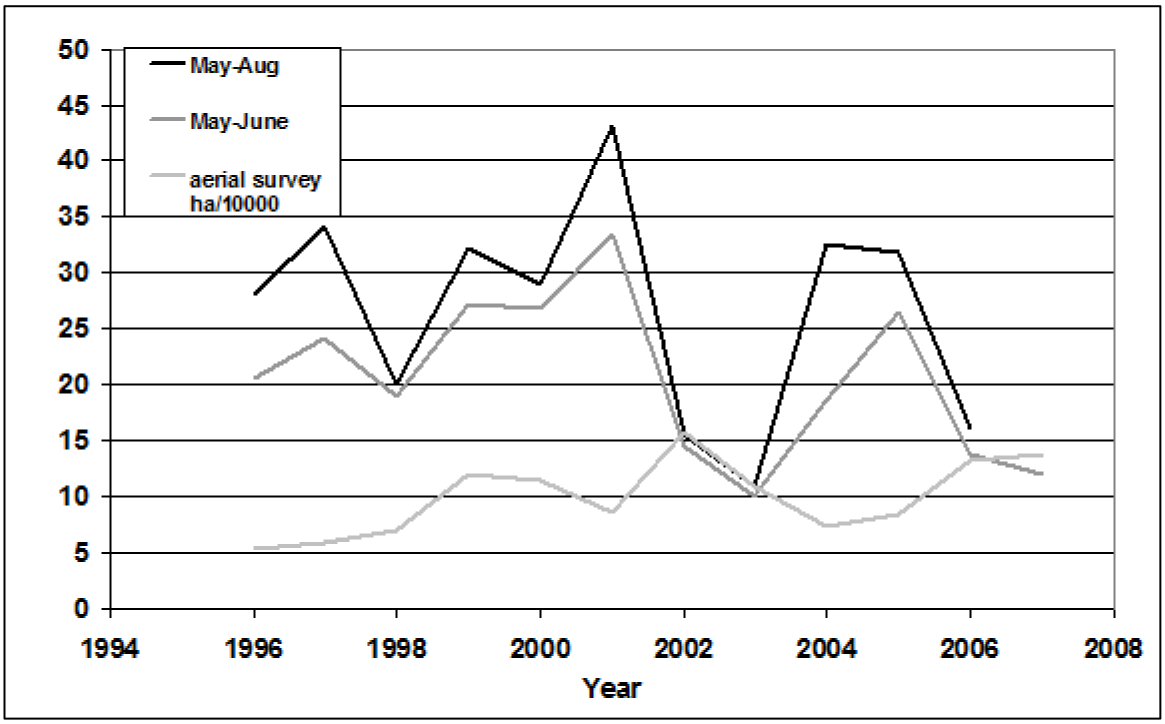

Figure 5. Average spring and summer precipitation at five weather stations throughout the study area superimposed on the number of symptomatic hectares/10000 identified by aerial survey.

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Climate of seed source affects susceptibility of coastal Douglas-fir to foliage diseases: results from a reciprocal transplant provenance study

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Introduction

The foliar pathogens *Phaeocryptopus gaeumannii,* the causal agent of Swiss Needle Cast (SNC), and *Rhabdocline* species, the causal agents of Rhabdocline Needle Cast (Rhabdocline), are two important pathogens specific to Douglas-fir (*Pseudotsuga menziesii).* These pathogens have been shown to disproportionately affect genetically maladapted seed sources, causing serious reductions in productivity. Understanding the variation in susceptibility to Swiss needle cast (SNC) and Rhabdocline is a critical component to successful plantation management. This study is the first to thoroughly investigate the variation in tolerance/resistance of Westside Douglas-fir to Rhabdocline needle cast, and, through the inclusion of populations and test sites which span much of the range of conditions experienced by Westside Douglas-fir, expands on the currently limited knowledge of the variation in resistance/tolerance to SNC.

In this experiment, we examined every tree in the Douglas-fir Seed-Source Movement Trial (SSMT), a large scale common garden, reciprocal transplant study established by PNW Research Station in collaboration with private landowners. We examined the relationship between levels of resistance and/or tolerance to SNC and Rhabdocline, the climate of the seed source and the climate of the planting environment.

Objectives

1.) Assess the variation in resistance and/or tolerance to SNC and Rhabdocline as indicated by infection level and disease symptom expression. 2.) Utilize climate transfer distances between the seed source and test site to model this relationship and obtain estimated probabilities related to these transfer distances. 3.) Obtain probability of SNC disease symptoms and Rhabdocline spp. infection in relation to predicted climate conditions of 2080 under both moderate (4.5 RCP) and high (8.5 RCP) emissions scenarios.

Methods

The SSMT consists of nine planting sites, with 120 open pollinated Douglas-fir seed sources (families) representing 60 populations from 12 different geographic regions ranging from northern California to southern Washington, from high elevation to the coast. These seed sources were planted at nine different test sites located on three latitudinal transects, one in southern Oregon, one in northern Oregon and one in southern Washington. All test trees present in the SSMT were assessed for infection levels of P.gaeumannii and *Rhabdocline* spp as well as disease symptoms associated with SNC and Rhabdocline (8,960 trees in total). Infection severity ratings were estimated based on the presence of fruiting bodies of each fungal pathogen. *P.*

gaeumannii severity was rated on both the north and south side of each tree on a secondary lateral branch on the fourth whorl from the top of the tree. Ratings were binary, 0 = 0-33% of the stomata occluded, 1 = 33% or greater of the stomata occluded. Rhabdocline severity was assessed on the north and south side of each tree but in relation to the entire crown. Ratings for Rhabdocline severity were also binary, 0= 0-33% of the crown displaying fruiting bodies and 1 = 33% or greater of the crown displaying *Rhabdocline* spp. fruiting bodies.

Crown density was used to assess symptoms of SNC and was rated with 0 corresponding to a sickly sparse crown lacking in needle retention, and a 1 corresponding to a full healthy crown. Although crown color and needle retention are also used to assess symptoms of disease, these attributes proved to be difficult to assess in 8 year-old trees and field assessment often was inconsistent. Using generalized linear mixed models and the probit link function, probabilities of moderate to severe disease symptoms and infection were calculated using differences between population source and test sites with respect to the climate variables May through September precipitation (MSP), mean winter temperature (MWT) and continentality. Models with the lowest AIC score were selected.

The probability of low crown density and *Rhabdocline* spp. infection was estimated using the HadGEM2 climate projection model under both moderate (4.5 RCP) and high (8.5 RCP) emissions scenarios projected to 2080. The models selected for crown density and *Rhabdocline* spp. infection along with the corresponding model coefficients were used to estimate these probabilities in relation to the projected climate conditions of 2080.

Results

No patterns were observed in the infection levels of P. gaeumannii (Figure 1). However, there was variation in disease symptom expression (crown density) indicating a tolerance rather than resistance to P. gaeumannii. Populations from low elevation and coastal regions of Washington and northern Oregon consistently displayed high P. gaeumannii infection levels and low probabilities of low crown density indicating a tolerance to this pathogen. Stark differences among populations from different regions were observed in relation to infection by Rhabdocline spp. (Figure 2). Populations from northern California, southern Oregon as well as populations from high elevation regions displayed high probabilities of infection while populations from low elevation and coastal regions of northern Oregon and southern Washington generally displayed low probabilities of infection by Rhabdocline spp.; many populations from these regions displayed little to no infection indicating resistance to this pathogen.

These differences are a function of a difference in climate between the population source climate and the climate of the test site.

Climate variables which are influential to the epidemiology of P.gaeumannii and Rhabdocline spp., specifically May through September precipitation, mean winter temperature, and continentality index, are influential to the susceptibility of populations to SNC and Rhabdocline.

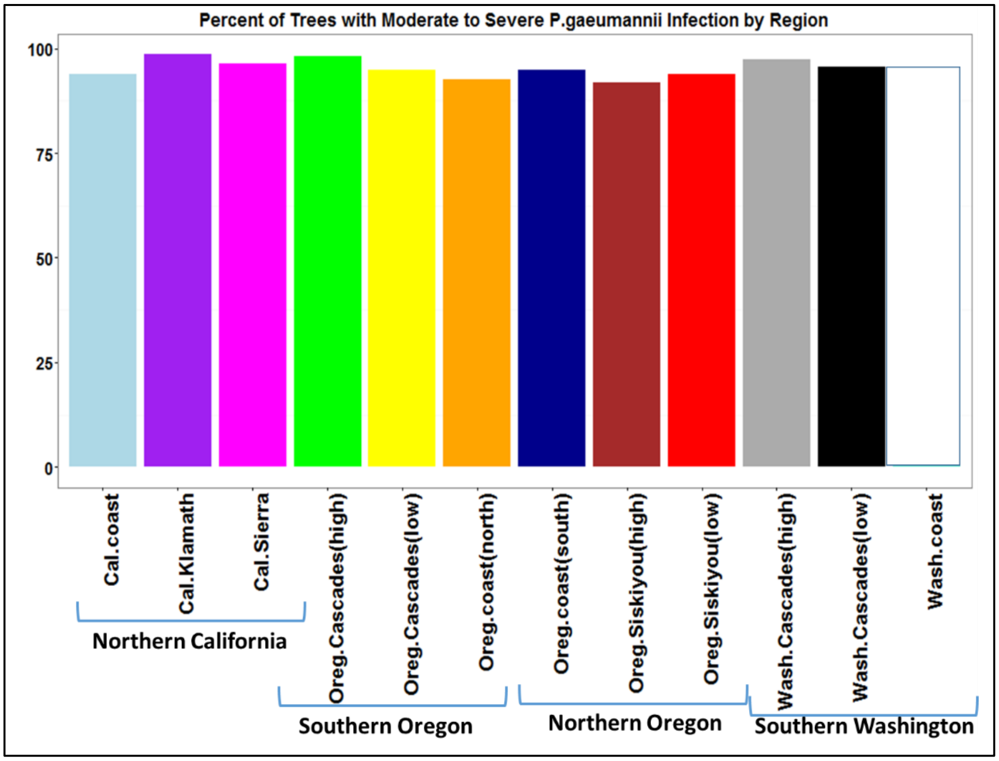

Figure 1. Percentage of trees within each region of the Douglas-fir Seed-Source Movement Trial (SSMT) displaying moderate to severe P.gaeumannii infection across all test sites in the SSMT.

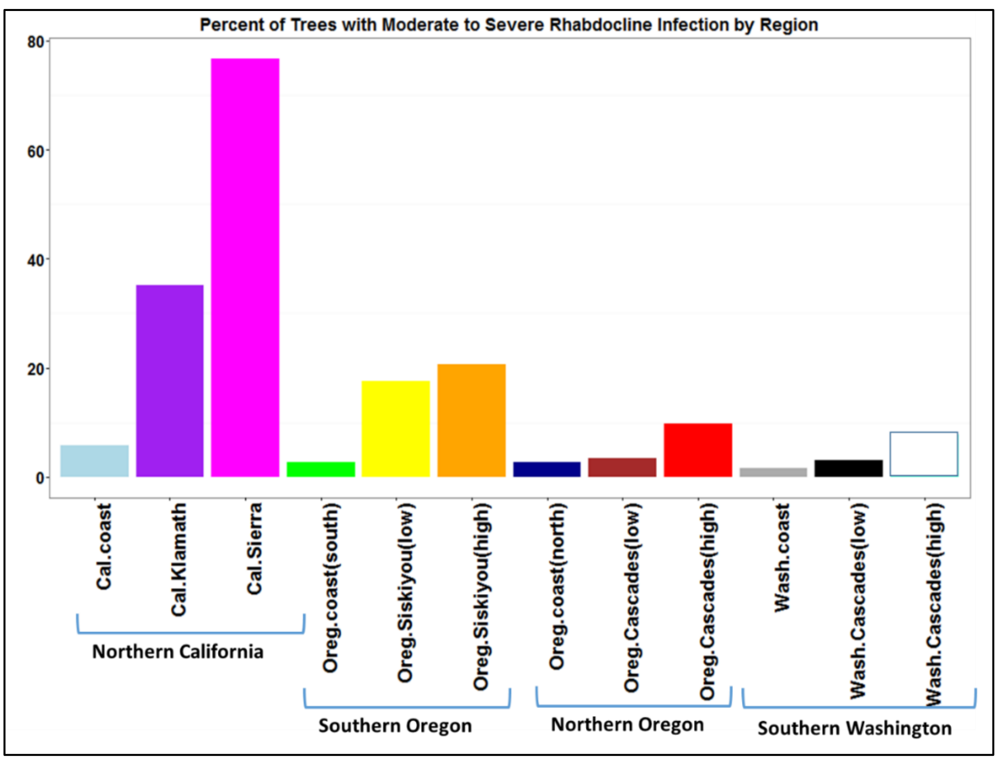

Figure 2. Percentage of trees within each region of the Douglas-fir Seed-Source Movement Trial (SSMT) displaying moderate to severe Rhabdocline spp. infection across all test sites in the SSMT.

Movement of seed sources from drier to wetter regions, as well as from cooler to warmer regions, will result in increased disease symptoms and severity.

Populations of source climates conducive to foliar pathogens, mild winter temperatures and high May through September precipitation, proved to be the most resistant/tolerant to Rhabdocline and SNC. Coastal seed sources exhibited the lowest probabilities of moderate to severe disease symptoms and Rhabdocline spp. infection, while high elevation populations and inland populations from southern Oregon and northern California exhibited the highest probabilities. May through September precipitation and mean winter temperature (MWT) proved to be most influential on the susceptibility of populations to these foliar diseases. Most importantly, transfers of populations from low to high MSP, and/or cool to warm MWT increased the probabilities of moderate to severe Rhabdocline spp. infection and SNC disease symptoms. Transferring populations 243mm in MSP (low to high) and/or greater than 4C° in MWT (cool to warm) resulted in greater than 25% probability of increased SNC symptoms. Transfers greater than 159 mm or greater in MSP (low to high) and/or 3°C or greater in MWT (cool to warm) resulted in greater than 25% probability of moderate to severe Rhabdocline spp. infection.

Populations from source climates most similar to that of the test site are the least susceptible to Rhabdocline and SNC.

Local populations consistently showed low SNC disease expression and Rhabdocline spp. infection. Therefore, local populations are generally well adapted to the disease pressure of their source climate. However, populations from high elevation regions consistently displayed high probability of SNC disease symptoms and Rhabdocline spp. infection when transferred to areas of higher winter temperatures as well as at their local test site.

Probability of Rhabdocline spp. infection and SNC disease symptoms will change in relation to the climate conditions of 2080.

Predicted climatic conditions in 2080 did not result in significant increases or decreases in probability of SNC disease symptoms or Rhabdocline spp. infection.

Discussion

Results from the current study indicate that populations from arid climates and climates of low winter temperatures are the most susceptible to SNC and Rhabdocline needle cast. These results urge caution in the transfer of drought tolerant populations of cool winters and dry summers to locations predicted to but not currently experiencing drought conditions. Transferring populations from low to high May through September precipitation and/or low to high mean winter temperatures resulted in increased probability of both SNC symptoms and *Rhabdocline* spp infection.

The probability of low crown density and *Rhabdocline* spp. infection are not estimated to change significantly in relation to projected climate conditions in 2080 under either moderate (RCP 4.5) or high (RCP 8.5) emissions scenarios. Therefore, local populations are predicted to remain adapted to the disease pressure of their local climate. However, increasing winter temperatures at high elevations may lead to increased losses due to Rhabdocline and SNC in high elevation Douglas-fir stands. High elevation populations were shown to be highly susceptible to *Rhabdocline* spp. infection and SNC disease symptoms when transferred to areas of warmer winter temperatures. Transfer of less susceptible low elevation or coastal populations into high elevation regions may offset losses due to increased pathogen presence in these locations. Adaptive traits such as cold hardiness should always be taken into account when making seed transfer decisions.

It is recommended that the climate transfers in this study, most importantly May through September precipitation and mean winter temperature, be taken into account when making reforestation and management decisions regarding seed transfer. Through this analysis we have created a method which land managers can use to obtain estimated probability of disease symptoms associated with SNC as well as probability of *Rhabdocline* spp. infection in relation to these climate transfers. Results of the current study urge caution in the transfer of Douglas-fir populations from dry spring and summer and/or cool winter conditions to mild, mesic environments as these transfers are associated with increased probability of SNC disease symptoms and *Rhabdocline* spp. infection.

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Relationships between Swiss Needle Cast Disease Severity and the Geographic Distributions of Two *Phaeocryptopus gaeumannii* Lineages

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Introduction

Spatial structure in plant pathogen populations and its influences on disease can provide valuable insights into landscape-level epidemiology, and inform predictive models and management strategies (Rieux et al. 2011). Initial assessments of the population structure and epidemiology of *Phaeocryptopus gaeumannii* identified two genetically distinct population groups and seemed to implicate one of them, Lineage 2, in the recent SNC intensification. The greater relative abundance of Lineage 2 where SNC symptoms were most severe suggested an "epidemic" population structure in which an abundance of relatively rare genotypes occur near centers of disease severity. This phenomenon might play a role in the SNC outbreak near Tillamook, Oregon (Winton et al., 2006). Winton (2001) observed that Lineage 2 was twice as likely to be detected in stands with severe SNC symptoms, and only half as likely to be detected in stands with less severe disease. It was also observed that stands with higher proportions of Lineage 2 had lower canopy densities and more chlorotic foliage (Winton 2001). Isolates collected from sites with severe disease also seemed to produce more severe symptoms, compared to Lineage 1 isolates, in inoculation trials. In an effort to better understand factors contributing to SNC emergence and the intensifying disease severity observed in the western Coast Range in Oregon, we are investigating the influence of the relative abundance of two lineages of *Phaeocryptopus gaeumannii* on pseudothecia density (PsD) and foliage retention (FR). The primary focus of this study is to correlate these estimates of SNC disease severity with the distribution of the two *P. gaeumannii* lineages across several hierarchical spatial scales to evaluate the strength of their relationships and make inferences about the relative aggressiveness of isolates of these two lineages. Ultimately, we are interested in evaluating whether the relative abundance of Lineage 2 is associated with greater disease severity.

Methods

Foliage Sampling

Douglas-fir foliage was collected from sites in a gridded plot network of privately-owned plantations in the western Coast Range in Oregon managed by the Oregon State University Swiss Needle Cast Cooperative (SNCC) (Ritóková et al. 2016). From May to June 2014 foliage samples were collected from nine SNCC sites occupying a range of distances 0-35 miles from the coast near Tillamook, OR as well as two sites 15-25 miles from the coast near Florence, OR, one site 25-35 miles from the coast near Florence, and two sites 25-35 miles from the coast in southwestern Washington for a total of 14 collection sites. In June 2015, nine sites were sampled in Washington including four sites along a (~W-E) transect from Queets, WA to Quinault, WA and five sites along a (~W-E) transect from Ozette, WA to Pysht, WA. Foliage was collected from five randomly selected 10–30-year-old Douglas-fir trees at each site, with second and third-year internodes sampled from secondary branches in the upper crown. The foliage samples were stored on ice during transport, then returned to the campus of Oregon State University and stored under refrigeration until processed within 72 hours after collection.

Isolation of P. gaeumannii from Infected Foliage

Needles with pseudothecia of *P. gaeumannii* protruding from the stomata were selected for ascospore isolations. Six randomly selected needles from each tree were attached to the lid of a 100 mm plastic Petri dish with double-sided tape, and suspended above the agar surface to allow ascospore discharge. After 48-72 hours, individual germinating ascospores were excised from the agar surface with the aid of flame-sterilized forceps and isolated onto 2% malt agar (MA) (Difco Laboratories, Detroit, MI). Site information, tree number, and a unique isolate number were recorded for each spore isolate. Ten to twelve ascospores were isolated from the Petri dishes corresponding to each tree such that the resulting sample collection included approximately 950 isolates from which a sub-sample was selected for microsatellite genotyping. Cultures were incubated at 17 °C for 2–6 months to allow sufficient growth for DNA extraction and permanent storage of fungal tissue.

DNA Extraction, PCR, and SSR Genotyping

Total genomic DNA was extracted from vegetative mycelium using the DNeasy Plant Mini Kit 250 (Qiagen, Hilden, Germany). The protocol followed the manufacturer’s instructions with the addition of an initial maceration procedure. Agar plugs extracted from *P. gaeumannii* cultures were added to cryogenic vials with sterile 2mm glass beads. The vials were briefly submerged in liquid nitrogen to freeze the agar plugs prior to the addition of the DNeasy extraction buffer AP1. The vials were then agitated at 5000 rpm for 60 seconds with either a Mini-Beadbeater-1 (BioSpec Products, Bartlesville, OK, USA) or MP Bio FastPrep-24 (MP Biomedicals, OH, USA)

For each isolate, SSR microsatellite loci (Winton et al. 2007) were amplified in three multiplexed PCR reactions. The multiplexed reactions contained primers modified with a fluorescent dye label. The sequences of the primers were identical to those described in Winton et al. (2007), but without the 18 bp M13 universal tails and the resulting amplicons were 36 bp shorter than those produced using those primers. The PCR reactions were performed using the Qiagen Type-It Microsatellite PCR kit with the protocol employed according to the manufacturer's instructions, but with reaction volumes of 12.5 µl. The amplification was performed on a PTC-200 thermal cycler (MJ Research, Inc. Waltham, MA, USA) programmed as follows: 95 °C for 15 min, 30 repeated cycles of 94 °C for 30 s, 57 °C for 90 s, and 72°C for 30 s, with a final extension of 60 °C for 30 min. The samples were then cooled to 4 °C.

Each of the multiplexed PCR reactions was diluted by a factor of 10 in deionized water and 1 µl of the diluted product was submitted to the Center for Genome Research and

Biocomputing (CGRB, Oregon State University, Corvallis, OR USA) for genotyping via capillary electrophoresis on an ABI 3730 DNA Analyzer (Applied Biosystems- ThermoFisher Scientific Corporation, Waltham, MA USA) with the GS-500ROX size standard. Allele sizes and genotypes were assigned with the aid of the ABI GeneMapper 4.0 software. Bins were set such that the samples could be de-multiplexed based on their sizes and fluorescent labels, and panels were set to recognize the allele size ranges reported in (Winton et al. 2007) adjusted to account for the absence of the M13 primer tails. Microsatellite alleles were called using the standard algorithm in the GeneMapper software and were also validated visually for each locus and isolate.

Data Analysis

Multilocus genotypes from a total of 845 *P. gaeumannii* isolates from 23 sites in northwestern Oregon and western Washington were included in the regional study. Data formatting and analyses were performed with R version 3.3.2 (R Core Team 2016) and Microsoft Excel 2011. The microsatellite allele data were formatted in Genalex 6.5 (Peakall and Smouse 2006, 2012) and imported to R for analysis. For all analyses described here, the mutlilocus genotype data were stratified in a population hierarchy, as described by Grünwald and Hoheisel (2006). The broader geographic regions were considered as the most inclusive level of this hierarchy with sites within regions and trees within sites.

Phylogeography

Maps depicting the geographic distributions of the two *P. gaeumannii* lineages across northwestern Oregon and Washington, with pie charts representing the proportions of each lineage recovered from each of the sampling sites, were constructed in R using the *mapplots* and *shapefiles* packages. A shapefile of the United States was used as the base map, and the function *draw.pie* was used to place the pie charts at the precise GPS location of each of the sampling sites.

Disease Assessments

Aerial survey maps for Oregon were produced by the Oregon Department of Forestry and USFS and reproduced from Ritóková et al. (2016). The aerial survey maps for Washington were produced by the Department of Natural Resources (WA DNR) and USFS. These maps show the distribution of SNC symptoms and provide estimates of their severity as red (severe) or yellow (moderate) polygons. Ritóková et al. (2016) provide a description of the aerial survey methods and results. Disease severity data for the sites in Oregon and southwest Washington were included in Ritóková et al. (2016) with pseudothecia density (PsD) expressed as the number of stomata on 2-year-old needles occluded with pseudothecia of *P. gaeumannii* out of a visual assessment of 100 stomata viewed at a magnification of 200x. FR was estimated for each of four needle age classes, and was rated on scale of 0-9 where 0 represents 0-10% of foliage retained, and 9 represents 90-100% of foliage retained. The pooled values for four-year FR and PsD were averaged for each tree and each site. The site-level PsD and FR ratings were then modeled as a function of the proportion of Lineage 2 recovered in a rarefied sample size. The strength and statistical significance of each of the associations was assessed with Pearson's product-moment correlation in the *stats* package in R (R Core Team 2016). The 37 trees included in these analyses are those from which five or more isolates have been genotyped.

Results

This study summarizes the distributions of the two lineages of *P. gaeumannii* at three spatial scales (region, site, and tree) in a hierarchical sampling scheme and relates these distributions to aerial survey results as well as two common measures of disease severity, FR and PsD. A total of 541 *P. gaeumannii* isolates from 37 trees across 14 SNCC sites in the western Coast Range in Oregon and southwest Washington were included in the site-level and tree-level disease severity assessments. An additional 304 isolates collected from 45 trees from nine WA DNR Olympic Peninsula sites were included in the regional analyses in which the maps depicting the distributions of the two lineages were overlaid on SNC aerial survey maps (Figure 1). Specific disease severity data (FR, PsD) from WA DNR sites sampled in 2015 were not available. The proportions of Lineage 2 recovered from these sites ranged from 0 to 77.4% (Figure 1b). The proportions of Lineage 2 isolates recovered from each of the 14 SNCC sites ranged from 0 to 79% of the total isolates from a given site, while the proportions of Lineage 2 recovered from each of the 37 trees included in this study ranged from 0 to 100%. The average FR at these sites ranged from 38 to 91.7%, while the tree-level FR ranged from 16.3 to 97.0%. The average site-level PsD ranged from 4.4 to 41.1%, and the average PsD on individual trees ranged from 0.76 to 55.1%.

Regional

An overlay of the map showing the distributions of the two lineages on the ODF SNC aerial survey map revealed that sites with the greatest disease severity near the coastal town of Tillamook, Oregon correspond to areas where both lineages occur. These sites also had the highest proportions of Lineage 2 (Figure 1a). However, the sites in the southern range of our sampling distribution, those that are 15-20 miles inland from Florence, Oregon consist of mixed populations (i.e. both lineages present) but do not appear to exhibit symptoms of SNC disease (Figure 1a). Regions where Lineage 2 was not detected in our sampling, at sites approximately 25-35 miles from the coast near Tillamook, Oregon also correspond with areas that do not exhibit SNC symptoms. Similarly, the WA DNR sites with the most severe symptoms also had the highest proportions of Lineage 2 and occurred near the coast. The inland sites, where Lineage 2 was much less abundant or was not detected, had moderate SNC disease severity ratings or exhibited no symptoms of SNC disease.

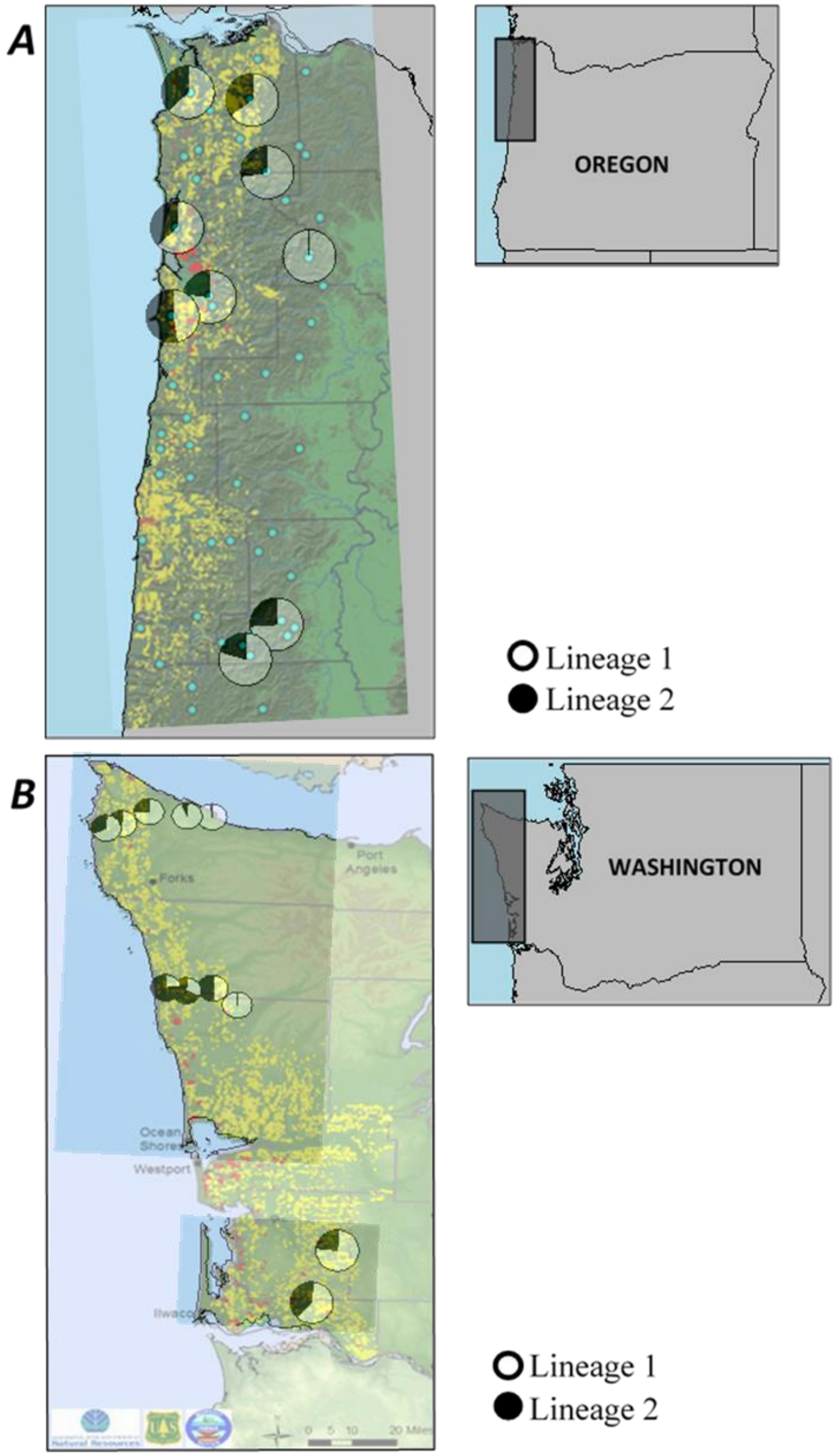


Figure 1. Map overlays showing the distributions of the two lineages of *P. gaeumannii* in relation to Swiss needle cast disease severity in **A)** Northwestern Oregon (aerial survey map with SNCC research plots from Ritóková et al. 2016). **B)** Western Washington (aerial survey map from WA DNR Forest Health Highlights 2015). Red polygons correspond to areas rated as having severe SNC symptoms, yellow polygons correspond to moderate SNC symptoms.

Site Level

Correlations between average PsD and FR, and the relative proportion of Lineage 2 at the site level produced statistically significant P-values, but had low Pearson correlation coefficients. When average PsD was modeled as a function of the relative proportion of Lineage 2 at the 13 sites for which PsD data was available, the resulting R^2 was 0.13 ($p = 0.041$) (Figure 2a). The relationship between average FR and relative proportion of Lineage 2 at all 14 sites was slightly stronger with an R^2 of 0.31 ($p < 0.001$) (Figure 2b). Despite the fact that sites with greatest relative proportions of Lineage 2 appeared to exist in regions where SNC disease severity was greatest on the aerial survey maps, the SNCC sites with the greatest proportion of Lineage 2 did not necessarily have the highest PsD or lowest FR, as would be expected if Lineage 2 was associated with greater SNC severity. Only 24% of the isolates at the site with the highest PsD in our study (T5-3, 41%) were identified as Lineage 2 (Figure 2a). Similarly, the sites with the lowest foliage retention also did not have the highest proportions of Lineage 2, but showed proportions of Lineage 2 ranging from 21-52% of the total isolates (Figure 2b).

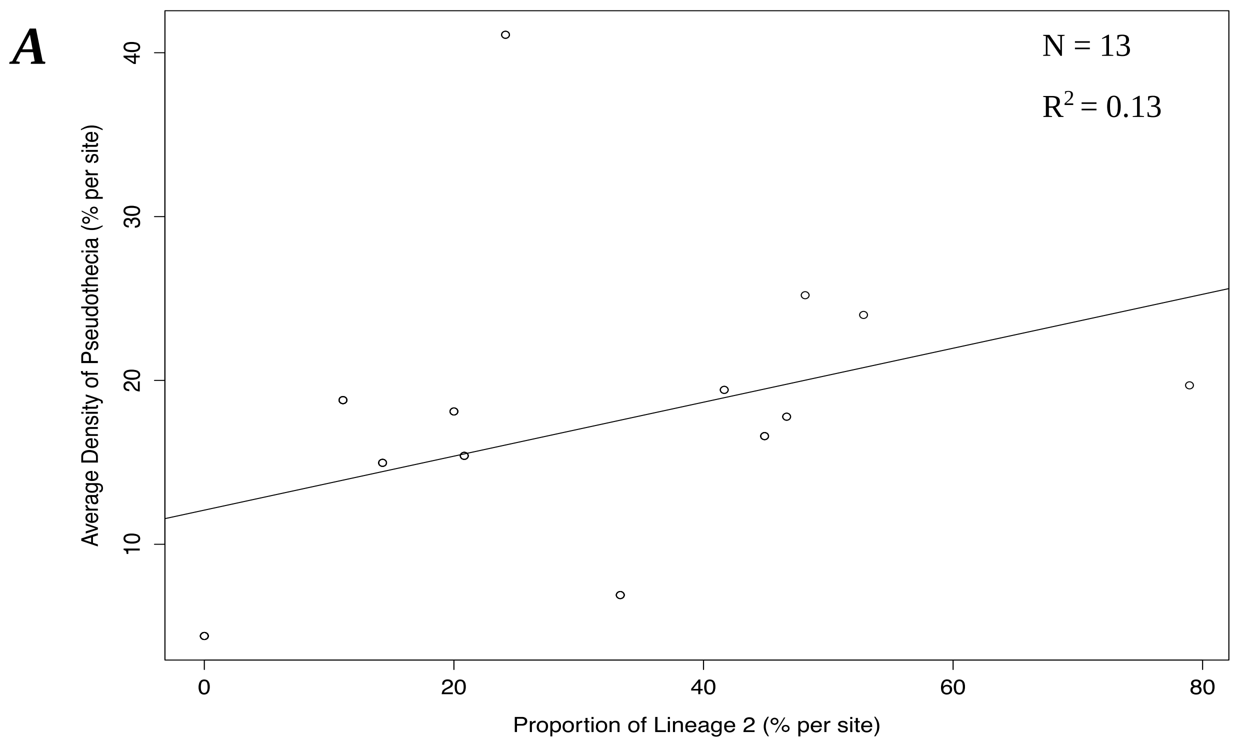


Figure 2. Scatterplots showing the relationships between the relative abundance of *P. gaeumannii* Lineage 2 (% of total isolates) and **A)** mean PsD (% of stomata occluded) at the site level, and **B)** Mean FR (% of 1-4-year-old needles remaining) at the site level. Correlation coefficients and P-values from Pearson correlation.

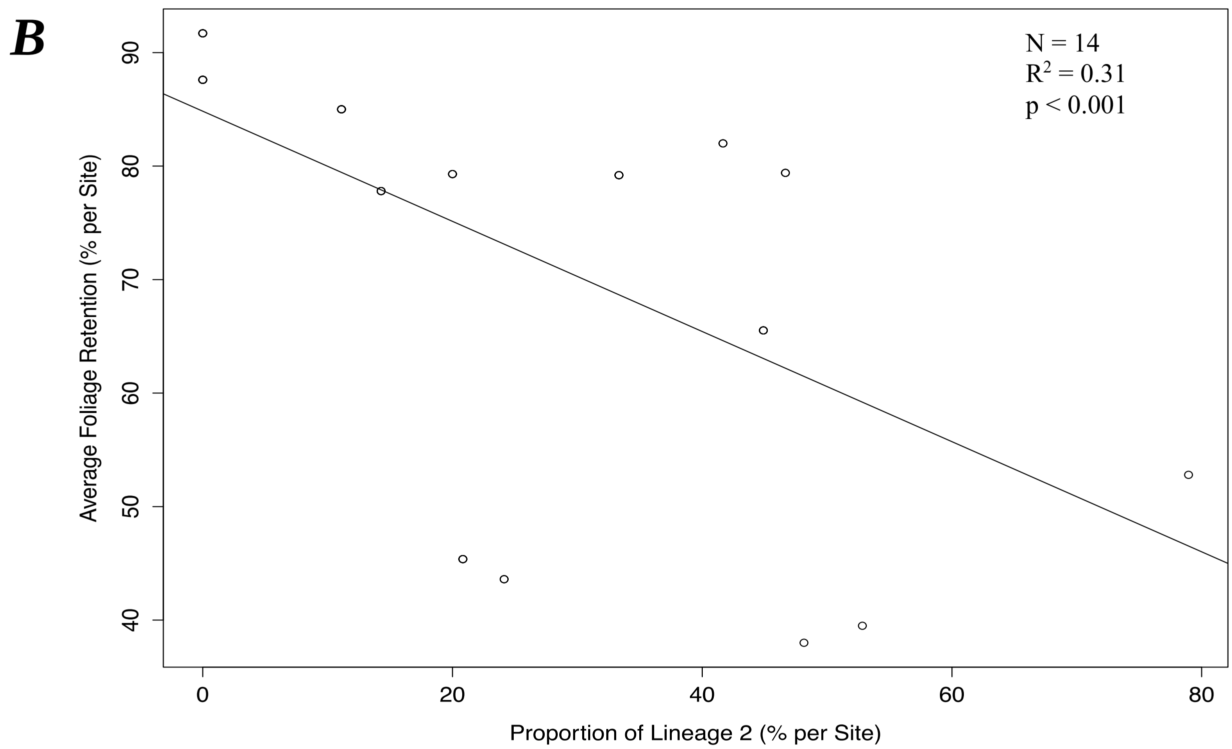
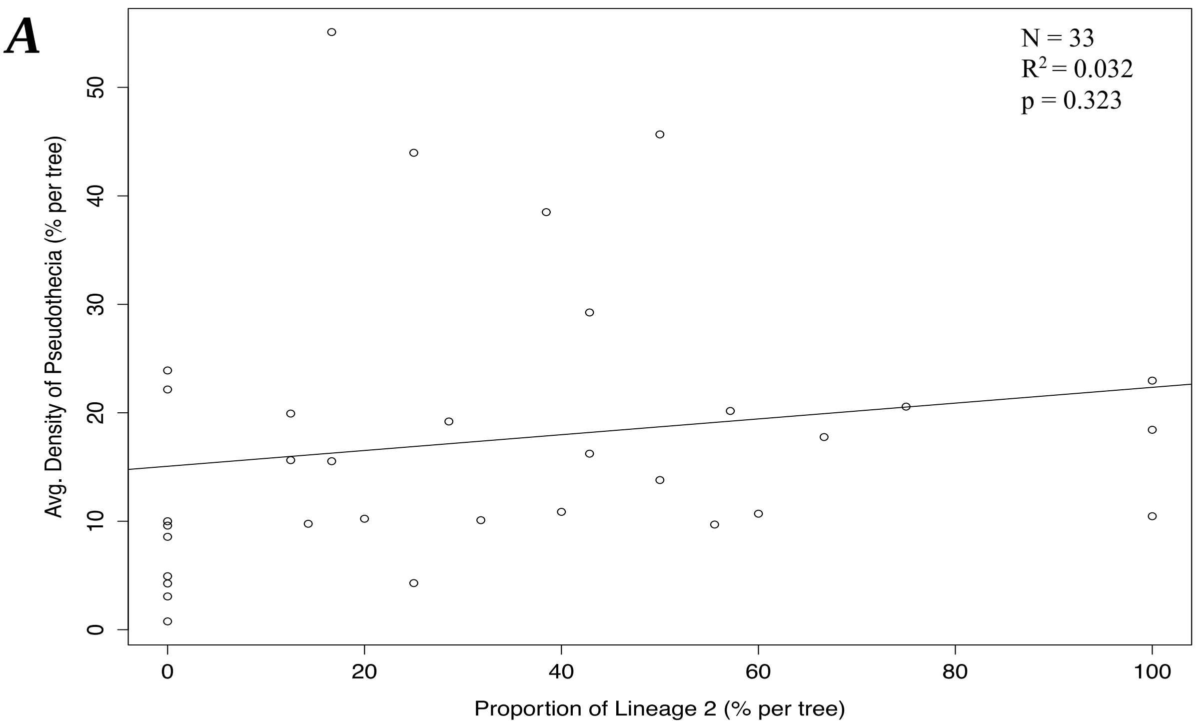


Figure 2. Scatterplots showing the relationships between the relative abundance of *P. gaeumannii* Lineage 2 (% of total isolates) and **A)** mean PsD (% of stomata occluded) at the site level, and **B)** Mean FR (% of 1-4-year-old needles remaining) at the site level. Correlation coefficients and P-values from Pearson correlation.

Tree-Level

Analyses modeling average tree-level PsD and FR as a function of the relative proportion of Lineage 2 isolates recovered from those same trees produced very weak correlations. The correlation between average PsD (from the 33 trees for which data was available) and the relative proportion of Lineage 2 in those trees was not significant ($R^2 = 0.032$, $p = 0.323$) (Figure 3a). The relationship between mean tree FR and the relative proportion of Lineage 2 in those trees was statistically significant, but with a weak correlation ($R^2 = 0.147$, $p = 0.019$) (Figure 3b). In agreement with the observation that sites with the largest relative proportions of Lineage 2 did not have the greatest mean PsD or lowest FR, trees from which the largest proportions of Lineage 2 were recovered did not have the greatest mean PsD or lowest FR. However, the same trends that occurred at the level of site also occurred at the level of the tree. For instance, trees with the largest mean PsD were those in which 17-50% of the isolates were Lineage 2 (Figure 3a). Trees with the smallest FR were those from which 25-50% of the isolates were identified as Lineage 2 (Figure 3b).



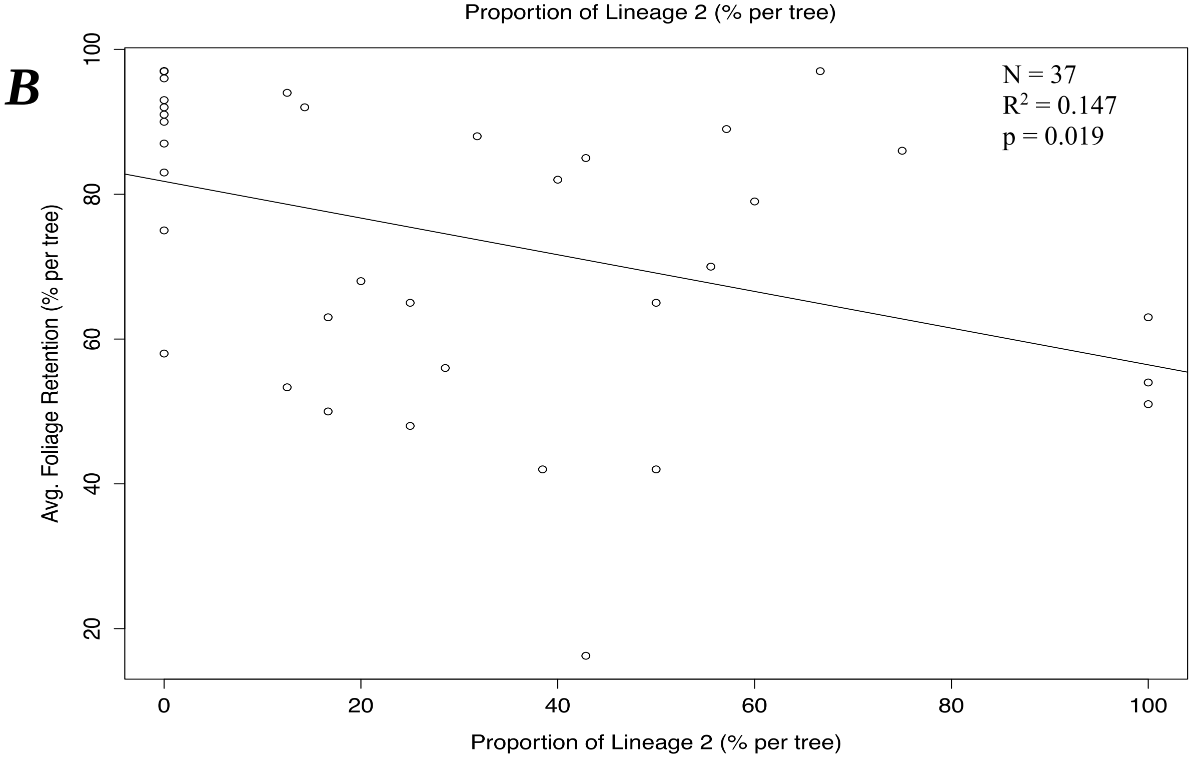


Figure 3. Scatterplots showing the relationships between the relative abundance of *P. gaeumannii* Lineage 2 (% of total isolates) and **A)** Mean PsD (% of stomata occluded) at the tree level, and **B)** Mean FR (% of 1-4-year-old needles remaining) at the tree level. Correlation coefficients and p-values from Pearson correlation.

Conclusions

This study aimed to evaluate the strength and statistical significance of relationships between the relative abundance of *P. gaeumannii* Lineage 2 and Swiss needle cast disease severity at three spatial scales including regional, site-level, and tree-level. While these relationships appear strong at the regional scale, they are much weaker at smaller spatial scales. While it has been recognized for some time that Lineage 2 occurs in the highest relative abundance in the western Coast Range in Oregon where SNC is most severe, comparisons between the geographic distributions of the two lineages described by Winton (2006) and quantitative measures of disease severity (i.e. PsD and FR) have not been made previously. The prevailing hypothesis that relative abundance of Lineage 2 is responsible for the severity of SNC occurring in northwestern Oregon seems tenuous given the results of the present study. It is possible, however, that the co-occurrence of these reproductively isolated lineages of *P. gaeumannii* has some influence on SNC disease severity. It is now known that these lineages co-occur within trees and within individual Douglas-fir needles (Bennett and Stone, unpublished). Whether this association between their co-occurrence and greater disease severity is due to synergistic effects, competition, or some other mechanism, should be the focus of future studies. The most likely explanation for the observed trends, given what is currently understood about the relationships between SNC disease severity and climate, is that Lineages 1 and 2 co-occur in high abundances in the western Coast Range where the climate is most conducive to fungal growth and reproduction and SNC disease is most severe. This hypothesis is supported by the observation that inland sites in the eastern Coast Range exhibit low SNC disease severity regardless of population structure, as in the case of sites 25-35 mi. east of Florence, Oregon sites where both lineages occur, or the inland Tillamook sites where Lineage 2 appears to be absent. These studies evaluating the population genetics and biology of *P. gaeumannii* in relation to SNC have contributed to our understanding of the factors influencing disease severity, and provided new information to support Douglas-fir management decisions.

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Relationship between canopy structure, microclimate, and Swiss needle cast severity among different ages of Douglas-fir forests

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Abstract

Swiss needle cast (SNC) is an endemic disease of Douglas-fir caused by *Phaeocryptopus gaeumannii*. The fungus infects newly emerged needles between May and August. As the fungus develops, its fruiting bodies (pseudothecia) block the stomata and inhibit gas exchange, reducing the photosynthesic rate in infected trees. Based on observations, SNC is more severe in young trees than in mature trees. We hypothesize that the complexity in mature forests contributes to different microclimates, a factor for needle infection susceptibility. Mature forests have more structural diversity and micro-environments than young forests. We are currently examining the relationship between canopy structure, microclimate and SNC severity (percent of stomata occluded by pseudothecia) among different ages of Douglas-fir forests.

Five paired young and mature forest sites were selected in 2015. In each site, 3 trees were climbed to sample needles from three canopy positions (lower, middle, and upper crown), and analyze the severity of SNC by counting the percent stomata occluded by pseudothecia. Mature tree crowns were measured and branch characteristics observed. Meteorological sensors were used to record temperature and humidity on lower, middle and upper canopy position.

Meteorological data and the crown structure data were collected in the field. The preliminary results in this report show SNC infection pattern between mature and young trees in 5 locations.

Study Area

Four stands were established on the west slope of the Cascades Mountains in western Oregon, specifically at Moose Mountain, Falls Creek, Toad Creek, and Soapgrass Mountain, and one stand in coastal Cascade Head (figure 1).

Methods

Field Sampling

For each study site, 3 trees were sampled in young stands (20-30 yrs old) and 3 trees in mature stands (120-450 yrs old). From each tree branches from 3 canopy positions (lower, middle, and upper crown) were collected, tree boles measured every 2 meters for taper and tree volume. Height, diameter, azimuth were recorded, and needle coverage for every branch more than 3cm diameter estimated.

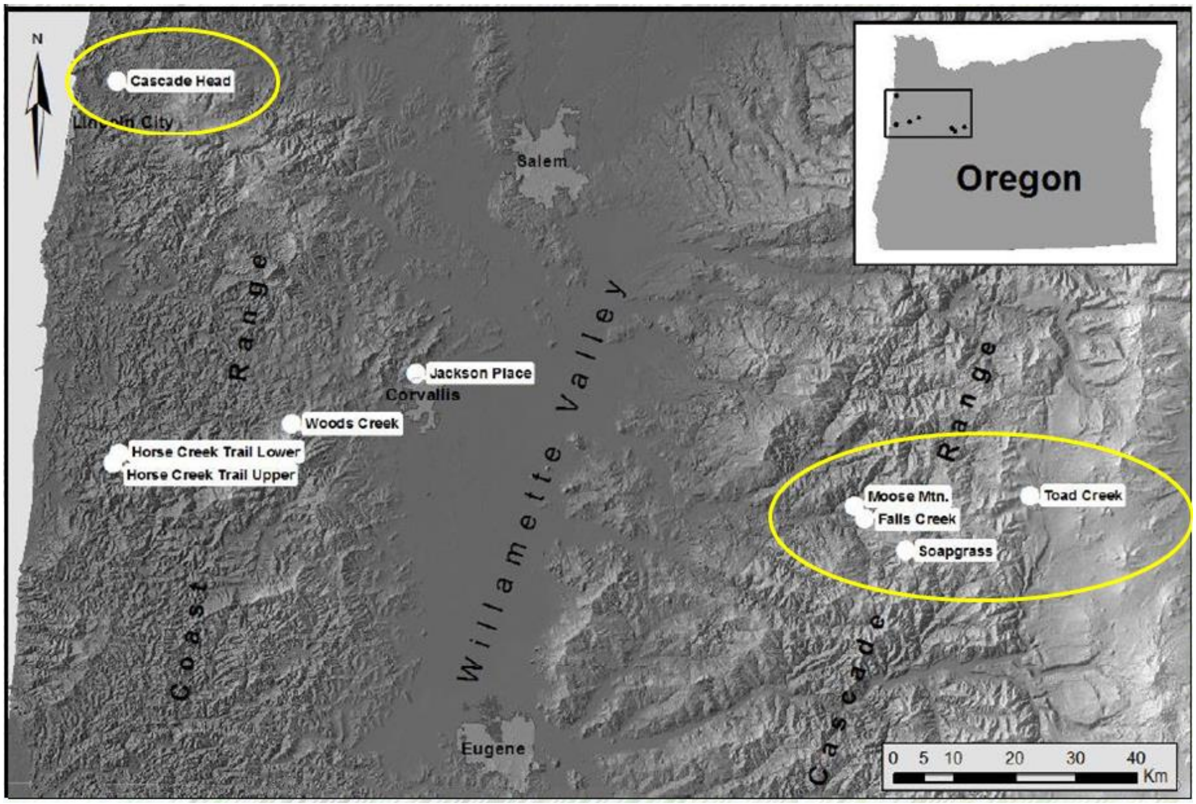

Figure 1. Study area. The map was created by Henry Lee.

To determine tree canopy microclimate, meteorological sensors were placed in the top of the tree and on the ground to record temperature and humidity. Leaf wetness sensors were positioned in low, middle and upper positions of the crown.

Lab methods

In the lab, 50 needles were randomly selected from every needle age-class (1-12 yrs) from each branch. Needles were taped on index card and stored at -20 ˚C.

For SNC incidence, needles of all age classes we observed under a dissecting microscope for presence or absence of occluded stomata. For SNC severity, ten 2-year-old infected needles were selected and 100 stomates observed for pseudothecial occlusion. Disease severity index was calculated by multiplying the percentage of occluded stomates and SNC incidence.

Preliminary Results

1) SNC infection incidence

The incidence was determined by the number of occluded stomata per 50 needles. Figure 2 shows the ubiquity of pseudothecia in mature and young trees in all sites with the exception of

Toad Creek, where the SNC incidence is low in both mature and young trees probably because of dry climatic conditions.

2) SNC infection index

SNC infection index is determined by percentage of occluded stomata multiplied by SNC incidence, to show the severity of SNC infection. SNC is more severe in young stands than in mature stands (figure 3). In Soapgrass Mountain and Toad Creek the index is low, most likely due to environmental conditions that are not suitable for fungal development - high altitude, dry summers and cold winters.

Work in progress

Meteorological data and canopy structure analysis have not been completed; we aim to compare data for the upper, middle and lower crown. Thus far, only one coastal stand has been compared to 4 Cascade Mountain Range study sites. To compare the coast and mountain range, in 2016, two additional study sites have been established on the Oregon coast: in Woods Creek and Klickitat Mountain. This study will contribute to understanding of SNC in mature coastal forests.

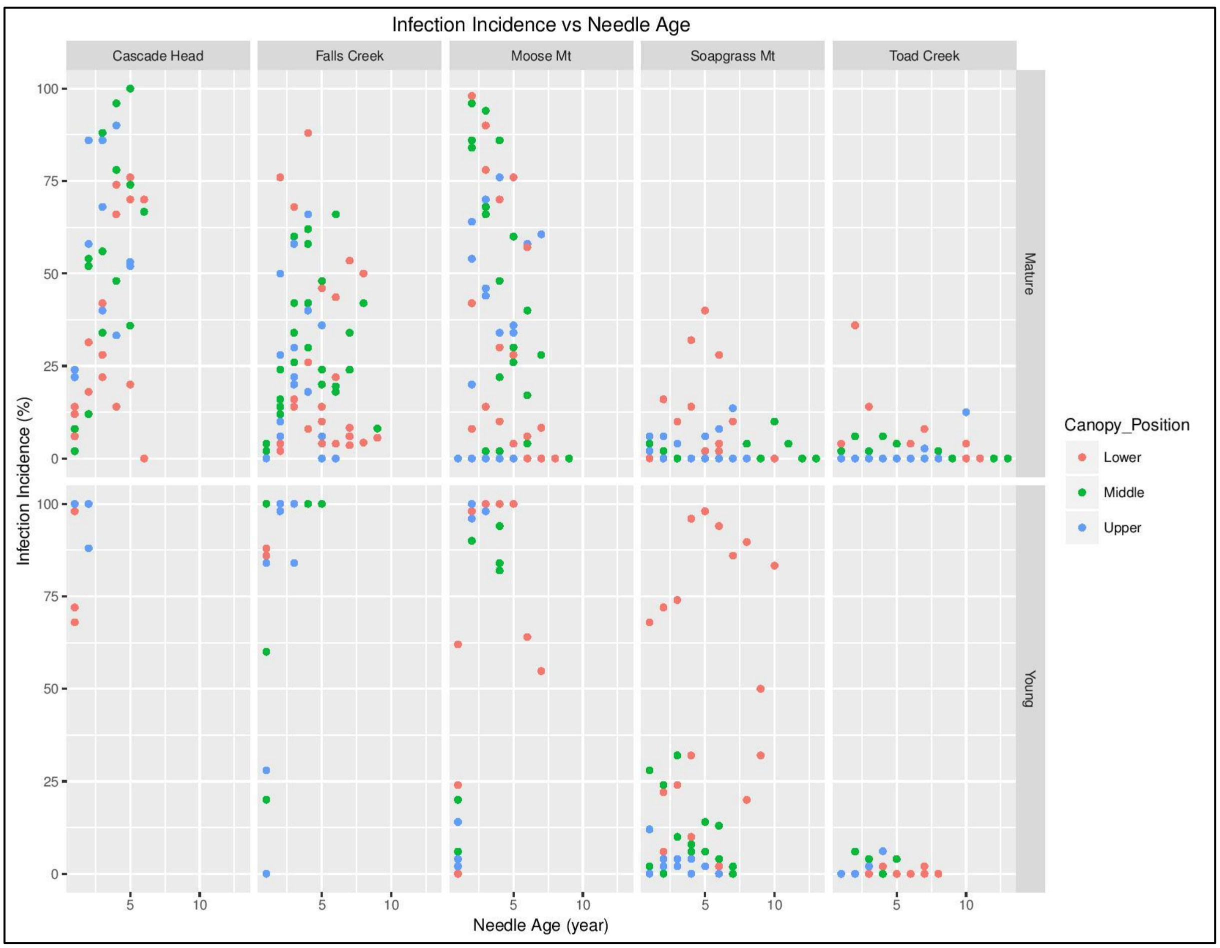

Figure 2. SNC infection incidence

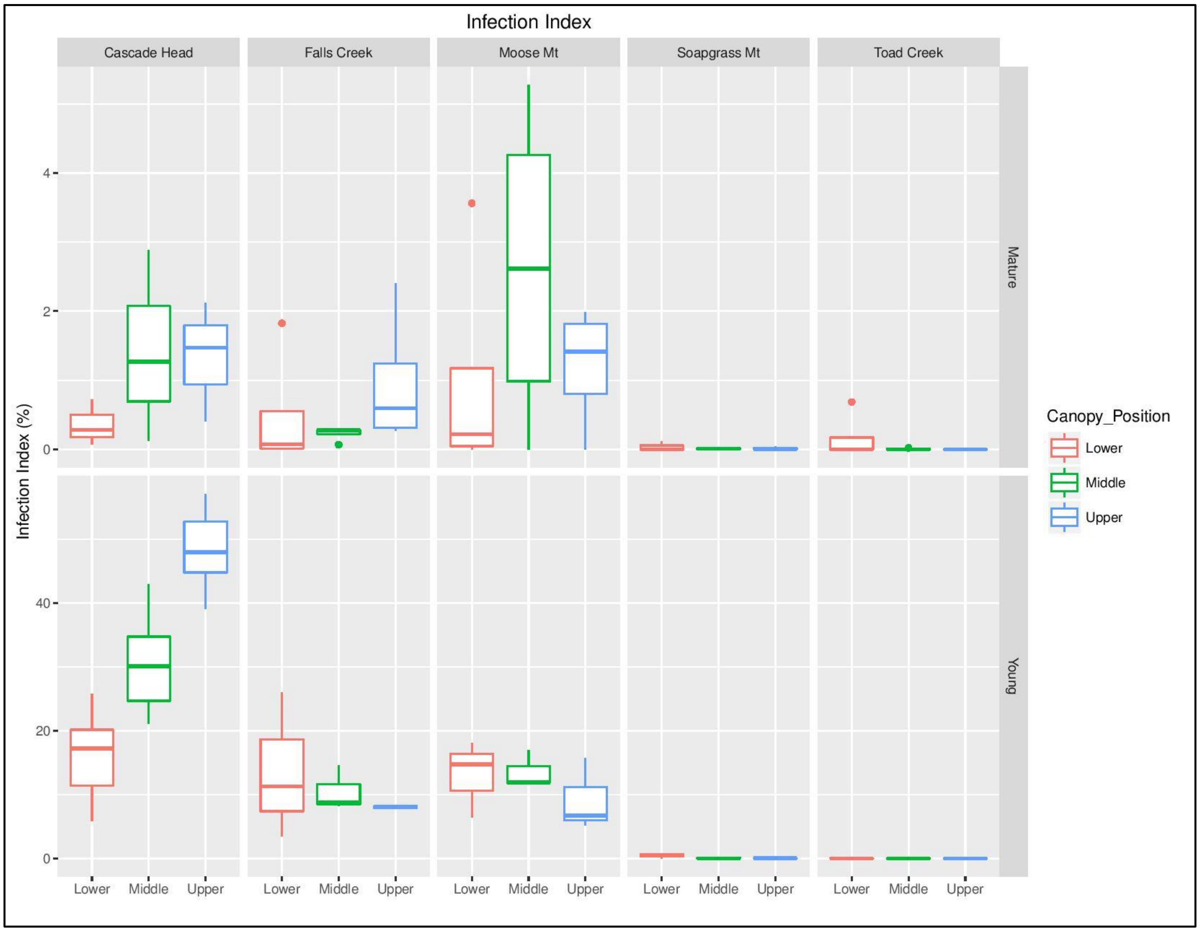

Figure 3. SNC infection index

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Article

Swiss Needle Cast in Western Oregon Douglas-Fir Plantations: 20-Year Monitoring Results

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Abstract: Swiss needle cast (SNC), a foliar disease specific to Douglas-fir (*Pseudotsuga menziesii*), is caused by an endemic Ascomycete fungus (*Phaeocryptopus gaeumannii*). In the late 1980s and early 1990s significant symptoms began to appear in coastal Oregon, and these have been associated with the planting of Douglas-fir in the Sitka spruce zone, leaf wetness during potential spore dispersal in May–August, and mild winter temperature. The first annual aerial survey was initiated in 1996 and has continued through 2015, which indicates a significant increase in area of visible symptoms from the air, increasing from 53,050 ha in 1996 to 238,705 ha in 2015. Monitoring plots in the NW Oregon Coast Range verified impacts of SNC on tree growth and productivity, with growth reductions averaging about 23% in the epidemic area linked to needle retention. A series of monitoring plots was set up in the western Cascade Mountains of Oregon and 590 10–23-year old Douglas-fir trees in 59 stands were tracked for 10 years, measured in 2001, 2006, and 2011. No measureable growth impacts were noted in this region of Oregon. A new plot network is being installed throughout the Oregon and southwest Washington coastal ranges as a means of monitoring future disease impact and providing framework for additional studies.

Keywords: Douglas-fir; foliage disease; Swiss Needle Cast; forest pathology; disease severity assessment; aerial survey

1. Introduction

Swiss needle cast (SNC), caused by the ascomycete fungus, *Phaeocryptopus gaeumannii* (Rodhe) Petrak, is the most damaging foliage disease of coastal Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) in the Pacific Northwest [1–3]. The fungus is native to western North America, and is common wherever the host tree is grown. It is known as Swiss needle cast because the disease was first noticed in Switzerland and Germany where Douglas-fir was planted in the early 20th Century. When North Americans subsequently checked native Douglas-fir stands, the fungus was common, but apparently caused no disease [4]. However, in the 1970's and 1980's the disease emerged in Christmas tree plantations in Oregon and Washington, and in the 1980's and 1990's became noticeable in forest plantations along the Pacific Coast. The disease intensified to the point that private forestland owners, federal and state agencies, in concert with Oregon State University together formed the Swiss Needle Cast Cooperative [5], a research cooperative, to investigate the disease epidemiology and determine best management practices [3]. Trees affected by SNC exhibit chlorotic foliage and premature needle loss, resulting in reduced height and diameter growth. Although healthy Douglas-fir generally hold a minimum of 3 years of needles, foliage retention of severely diseased trees can be very low (<2 years), and sometimes needles will be present only on new growth. It has been determined through a growth impact monitoring plot network in the northwest Oregon Coast Range that volume growth across the area was reduced 23%–50% by SNC [6].

P. gaeumannii asci are found in pseudothecia, which are black round-shaped fruiting bodies emerging from stomata on the underside of Douglas-fir needles. The life cycle of *P. gaeumannii* is completed only on live Douglas-fir foliage when pseudothecia release ascospores after maturity, in the spring and early summer. *P. gaeumannii* does not produce asexual spores (conidia) and thus is considered to have monocyclic lifecycle. Dispersion of spores occurs via wind and water splash. Pseudothecia are produced on foliage each year after infection, with increasing numbers until the needles are cast [1]. Infection occurs between early May and late July, after budbreak and during shoot elongation. Newly emerged needles serve as a primary substrate for new infection by ascospores [7]. After infection, fungal hyphae colonize intercellular spaces within needles as long as needles remain attached. In the laboratory, pseudothecia have been observed 2 months after exposure to inoculum [7] under conducive environmental conditions, but can take as long as 4 years to mature when the environment is not suitable for fungal growth. Where SNC incidence is low, fruiting bodies may be observed on 3 year or older needles, whereas in areas suffering epidemic levels of disease, blocked stomata are usually detected in the first spring following shoot production.

The primary mechanism of pathogenicity has been linked to physical obstruction of stomata, which prevents both CO_2 uptake and transpiration needed for photosynthesis [8,9]. With 30%–50% occluded stomata, the carbon sink exceeds carbon source and these needles are cast to prevent further loss [10]. SNC disease expression is highly correlated with increased numbers of pseudothecia obstructing stomata on DF needles [9,11], although Temel et al. [12] have shown that in some instances a tree can have high pseudothecial occlusion and express little disease. Disease epidemiology and landscape correlation studies have linked SNC disease development to mild winter temperature (low elevations) and leaf wetness during the spore dispersal period (May, June, July, and possibly August). Several modeling groups have focused on these characteristics.

In 1996 a cooperative aerial detection survey was begun to determine the spatial extent of disease. Run continuously since, the survey program has produced a 20-year record of disease symptoms in Oregon. In addition, a set of permanent growth monitoring plots was established throughout the NW Oregon Coast Range [2], as was a monitoring program in the Oregon Cascades. Although defoliation from SNC occurs in the foothills of the northern Cascade Mountains of Oregon, it is less damaging than in the Oregon Coast Range probably because of climate and other site factors. In 2001, baseline monitoring plots were established in 59 stands representing 810,000 hectares in the Cascade Mountains in Oregon using USFS-Forest Health Monitoring funding. Our objectives are to report on the 20 years of SNC aerial monitoring and 10-year plot monitoring in the Cascade Mountains, both aimed at assessing the threat to Douglas-fir forests in western Oregon, USA.

2. Materials and Methods

2.1. Aerial Survey

Aerial surveys using fixed-wing aircraft have been conducted annually from 1996 to present (2015) by the Oregon Department of Forestry and US Forest Service, Cooperative Aerial Survey in the Oregon Coast Range (Figure 1) [13]. The observation plane flies at 450 to 600 m above the terrain, following north-south lines separated by 3.2 km. Observers look for areas of Douglas-fir forest with obvious yellow to yellow-brown foliage, a symptom of Swiss needle cast. 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. Each polygon is classified for degree of discoloration as either "S" (severe) or "M" (moderate). Polygons classified as "S" had very sparse crowns and brownish foliage (Figure 2), while those classified as "M" are predominantly yellow to yellow-brown foliage with slightly denser crowns (Figure 3) than those classified as "S". The survey area extended from the Columbia River to the southern border of Curry County, and from the coastline eastward until obvious symptoms were no longer visible. In 2015, over 1.5 million hectares were surveyed in western Oregon.

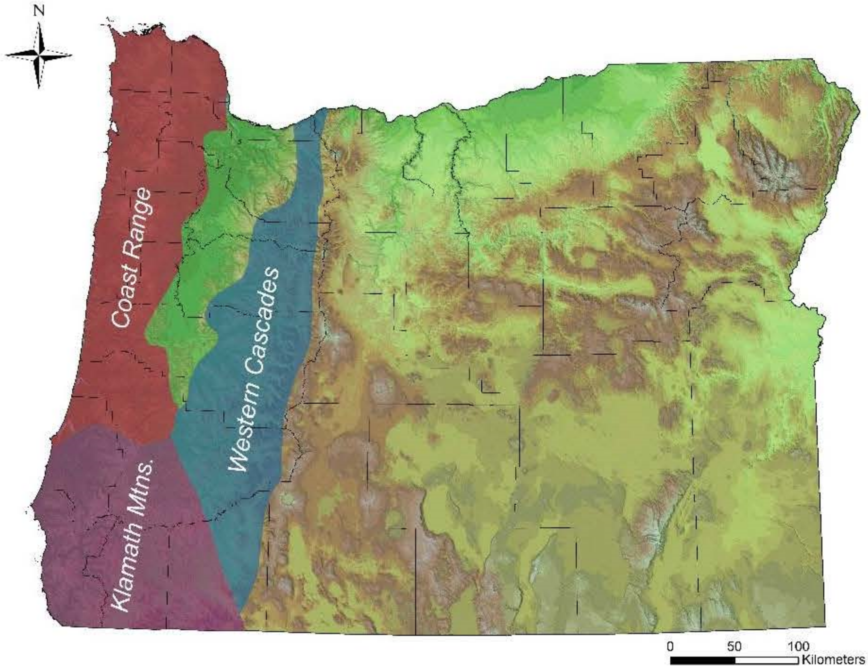

Figure 1. Mountain ranges of western Oregon, USA.

Figure 2. Mixed species stand with severe SNC infection (brown foliage). Light green trees are hardwoods (red alder).

Figure 3. Mixed species stand with moderate SNC symptoms (yellowish foliage). Light green trees are hardwoods, mostly red alder, dark green trees are Sitka spruce and Western hemlock.

2.2. Cascade Mountains Plots

In 2001, 59 stands that were 10-to 23-years old and contained more than 50% Douglas-fir were systematically located on public and private lands in the western Oregon Cascade Mountains [14]. Transects were established in a location representative of each stand based on aerial photos and slope, and aspect along with geographic location were noted. Ten Douglas-fir trees were sampled per stand for a total of 590 trees. At each plot, the nearest co-dominant or dominant Douglas-fir on each side of the transect was selected. Branches were sampled at mid-crown for foliage-retention and stomatal occlusion associated with SNC. Each stand had one transect with five sample plots located at 15.24 m intervals. Data collected for each tree in 2001 included: (1) stand, plot, and tree no.; (2) diameter at breast height (DBH, at 1.37 m); (3) total height; (4) height to lowest live branch; (5) ocular estimation of foliage retention in the mid-crown (0 to 8 years); and (6) foliage–retention index calculated for each sampled branch.

A foliage-retention index was calculated for each sample tree as follows: a live branch at mid-crown was selected on the south side of the sample tree and cut from the stem with a pole pruner. For trees with a mid-crown height >7.6 m. (most trees in 2011), the tree was climbed, and the selected branch was removed with a hand saw. From the cut branch, a secondary lateral branch that was at least four years old was selected, and the amount of foliage remaining in each needle age class (up to 4 years) was rated and recorded as: 0 = 0 to 10% of full complement present, 1 = 11% to 20% present, 2 = 21% to 30% present, ... 9 = 90% to 100% present. Ratings were summed for a minimum score of 0 and a maximum of 36 for each branch. Foliage retention has been shown to be the most reliable and efficient variable when estimating SNC severity in terms of tree volume-growth loss [1,6,14]. Foliage retention estimates from the mid-crown are considered more reliable than upper or lower-crown estimates, especially in larger trees. From April to July in 2006 and 2011, the 59 stands were resampled. Late spring and early summer, the period immediately prior to budbreak, are considered best for estimating foliage retention.

In 2011, for all 10 sample trees per stand, foliage from the cut branches was placed in a sample bag, labeled with stand and tree number; and processed in the Weyerhaeuser laboratory in Centralia, WA, USA, for pseudothecial counts and foliage retention. The pseudothecial counts in 2006 and 2011, were determined by placing needles under a camera (Big-C Dino-Lite Pro AD413T (USB) 12×~200× (BigC Dino-Lite Digital Microscope, 19803 Hamilton Ave. #200, Torrance, CA, USA), connected to a laptop computer, and the percentage of occluded stomata was recorded at 200× magnification. Foliage retention over the last four years also was calculated in the lab in the same manner as was done in the field on a scale of 0 to 36.

Some stands were thinned and because stand density can influence tree growth, total basal area/ha and basal area/ha of Douglas-fir were calculated in 2006 and 2011 around one tree at each of the five sample points. Total plot basal area was measured around each sample tree by counting all in-trees with a 10-factor prism and multiplying by a basal-area factor of 10. All trees ⩾ 2.5 cm. DBH of any species were counted. All data were entered into an Excel spreadsheet where R^2 values were calculated from selected graphed data.

3. Results

3.1. Aerial Survey

The 1996 cooperative aerial survey detected 53,050 ha displaying visible symptoms of SNC, which increased until 2002, peaking at 156,630 ha (Figure 4). The disease abated during the next two years, but from 2004 until 2015 the disease has steadily increased, reaching a high of 238,705 ha in 2015. Visible symptoms have generally been limited to within 50 km of the coast (Figure 5).

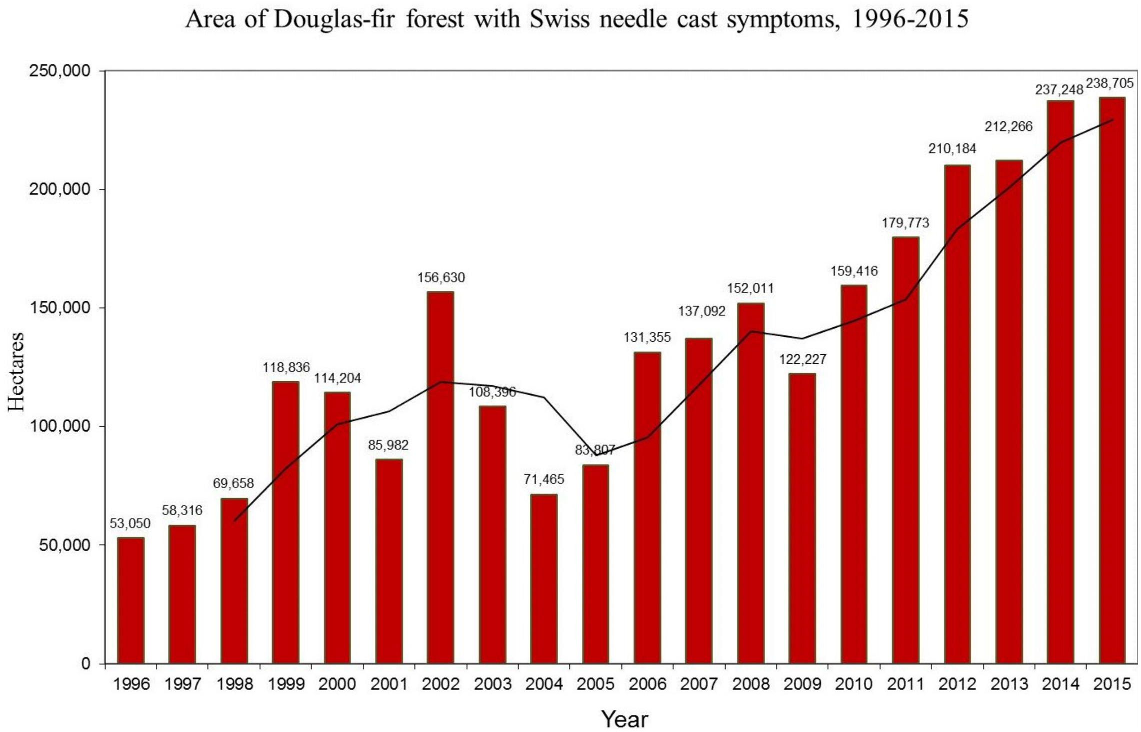

Figure 4. Area of Douglas-fir forests with Swiss needle cast symptoms determined from aerial survey in late spring from 1996 to 2015 (20 years).

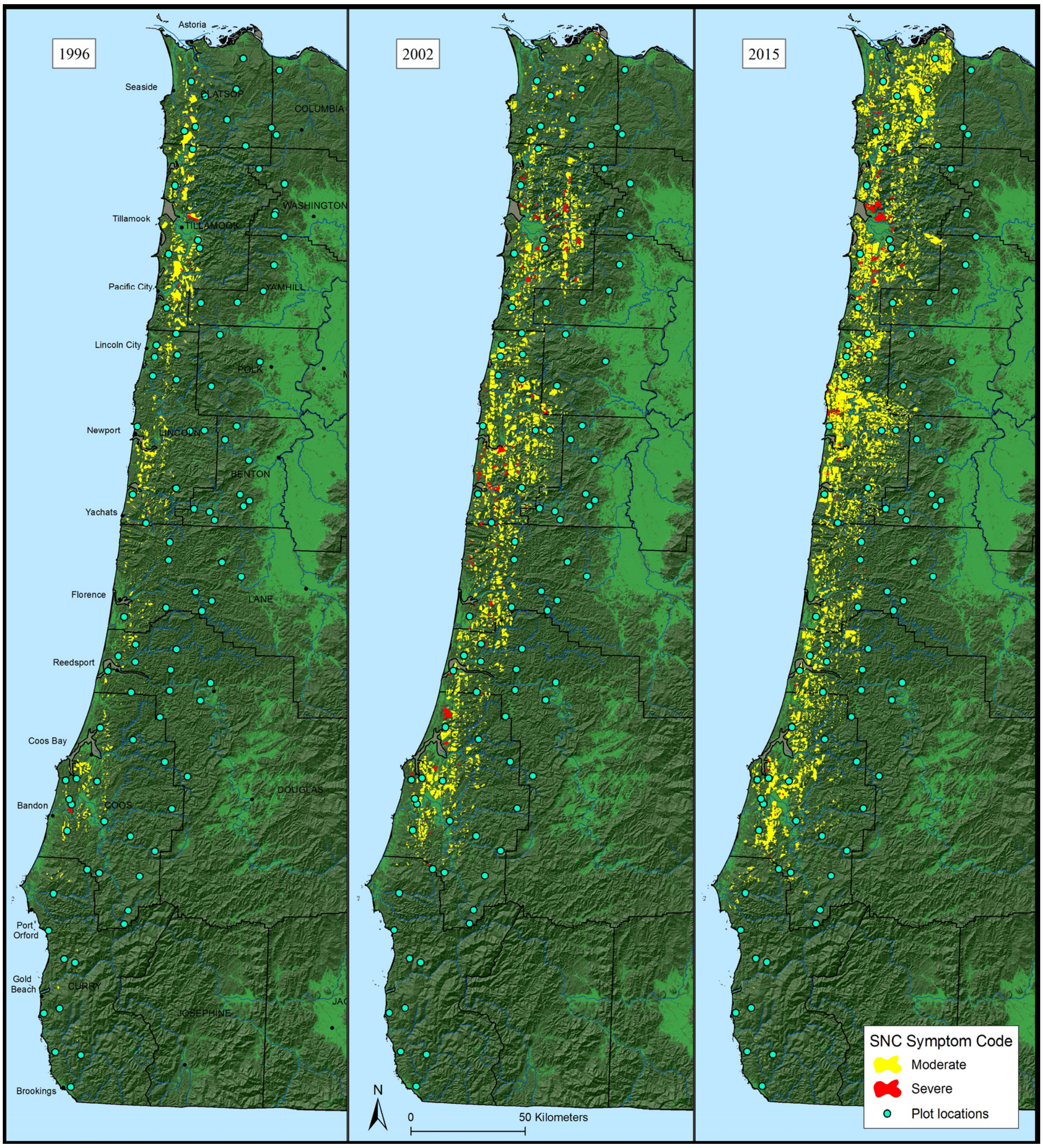

Figure 5. Spatial pattern of Swiss needle cast-symptomatic Douglas-fir in the Coast Range of Oregon as determined by aerial detection survey in 1996, 2002, and 2015. Yellow indicates moderate symptoms, while red indicates severe symptoms. The blue dots represent new plot network.

3.2. Cascade Mountains Plots

Ground-based estimates of mid-crown–foliage retention increased by 1.2 years (range −0.7 to 3.1) from 2001 to 2011. In 2006 and 2011, many trees had a partial fifth-year complement of needles and some trees as many as 8 years of needles, but these were not reflected in retention indices that scored only the last 4 years of needles. Mid-crown-foliage ratings did capture 5 to 8-year-old needles. Correlations between field foliage-retention index and mid-crown foliage-retention years were moderate at $R^2 = 0.68$, $p < 0.0001$ in 2001, 0.54, $p < 0.0001$ in 2006, and 0.46, $p < 0.0001$ in 2011. Mid-crown foliage retention averaged 4.7 years, and only three stands had <3 years of foliage in 2011.

Mean percentage of stomata occluded by pseudothecia was 8.7% for 2-year-old needles sampled in 2011; this needle cohort was infected as new growth after budbreak in 2009. There were no stands with mean stomatal-occlusion densities >34% in 2011. Correlation between 2011 lab foliage-retention index and 2-year-old needle stomata occlusion was moderate at R^2 = 0.36, p < 0.0001. Other factors besides occluded stomata, such as tree genetics and soil-nutrient levels, are known to affect foliage retention. There was a moderate correlation between stand elevation and either 2011 foliage-retention index (R^2 = 0.38, p < 0.0001) or 2009 (2-year-old) needle-stomata occlusion (R^2 = 0.54, p < 0.0001) (Figure 6). In general, there was more foliage and fewer pseudothecia at higher elevations.

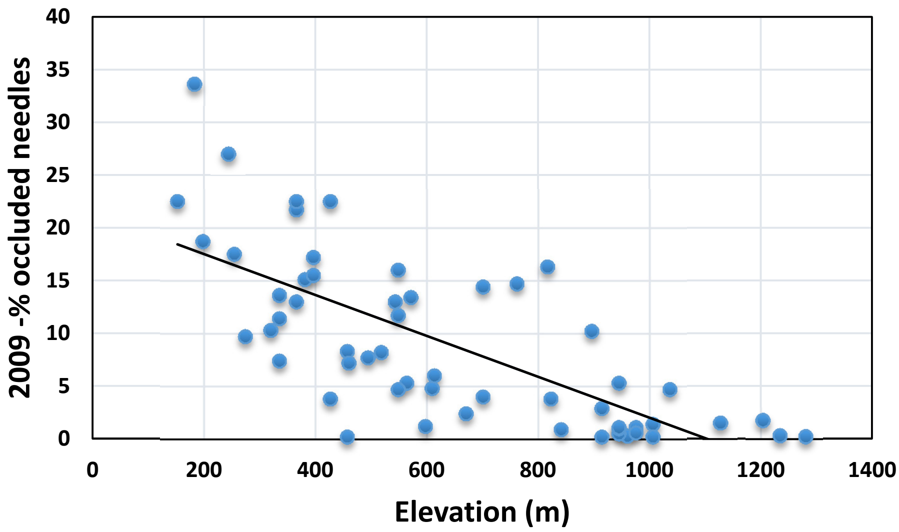

Figure 6. 2009 (2-year-old) needle-pseudothecial density vs. elevation. R^2 = 0.54, p < 0.0001.

Correlation between indicators of SNC (2011 mid-crown foliage retention, 2011 foliage retention index, and 2009 (2-year-old) needle stomata occlusion) and growth were generally insignificant, with the exception of 2009 (2-year-old) needle-stomata occlusion and total-height growth (p = 0.01, R^2 = 0.11).

4. Discussion

The increasing area observed (Figure 4) and landscape pattern of the Aerial Detection Survey (Figure 5) from 1996 to 2015, indicate an intensifying disease epidemic in the Oregon Coast Range. Several studies and plot networks have documented growth impacts across the region, with general estimates for the epidemic area north of Newport, Oregon, south of Astoria, Oregon and west of the crest of the Oregon Coast Range at about 23% reduced growth for plantation Douglas-fir [2,6]. A new research and monitoring plot network is currently being installed from the California border to SW Washington and inland about 50 km (35 miles) from the coast by the SNCC [15,16] that will allow broader inference about impacts to tree growth, as well as epidemiology research. Although, the Oregon Cascades Plots indicate no extensive problem along the west slope of the Oregon Cascade mountains, recent reports from landowners (2013 and 2014), site visits by the authors, and a short opportunistic aerial detection flight in June 2015 indicate that some stands in lower elevations of the western Cascade mountains are showing symptoms of SNC, including chlorosis in spring and low foliage retention (~2 year). Therefore, concern is mounting that SNC impacts are not abating, and may be a continuing and increasing threat to Douglas-fir plantation productivity in the Douglas-fir region.

Because it is a ubiquitous native fungus everywhere Douglas-fir grows, disease intensity is associated with host age class structure and environmental setting and climate [1,11,17,18]. Only current-year foliage is colonized, and there appears to be no resistance to infection by the tree [19,20]. The fungus may be characterized as an endophyte or biotroph [9] because it does not kill cells of the leaf, and disease is caused when stomates of one- and two-year old leaves are occluded. Carbon uptake is directly related to percent of stomatal occlusion [9]. Disease emergence is associated with increased colonization of needles, stomatal plugging, inoculum load, loss of needles, needle chlorosis, and reduced growth. Nonetheless, to date SNC does not cause tree mortality [2].

The epidemiology of disease has focused on seasonal patterns of temperature and moisture [11]. Numerous climate-disease models have been developed. Depending on the model, disease symptoms (needle retention, growth loss) are associated with warm winter (December–February) [11], March–August mean monthly temp [20], distance from coast [17], or continentality index [21]. Lee et al. [22] contend that winter conditions are important at cooler, wetter sites, and that summer conditions are more important at less humid, warmer sites. Warm winter and spring weather may allow for increased growth of the fungus within the needle, and therefore earlier formation of stomata-plugging pseudothecia. Leaf wetness, humidity, and rainfall during spore dispersal in May–August is also important and is associated with improved fungal germination. Needle retention is correlated with growth as well as disease severity [1,2,6,11]. Therefore, most models focus on needle retention because it is easier to evaluate in the field and correlates well with tree growth. Maguire et al. [2,6] have shown that tree growth is directly related to needle retention and when needle retention drops below 3.2 years, growth loss is proportional to needle retention, with 2 years of needle retention estimated to be associated with 30% growth reduction. Spatial landscape patterns of needle retention have been estimated by several modeling groups [22–25].

The intensification of SNC in the Oregon Coast Range during the last 20 years is likely the result of complex interactions between biotic, abiotic, and management factors. Early in the epidemic it was observed that foliage loss appeared greater in upper crowns rather than the more typical pattern caused by foliage diseases [1,18]. Most foliage diseases cause needle loss in the lower and inner crown, where humidity is greatest. The general springtime ubiquity of moisture throughout the Oregon Coast Range would suggest that leaf wetness is not a limiting factor in the current zone of the SNC epidemic. Warm winter temperatures are negatively correlated with elevation, and are lowest near the coast and river valleys and generally increase with distance from coast. Another factor influencing SNC is it's positive correlation with soil N concentration and negative correlation with soil Ca, both of which are also associated with proximity to the coast [26]. The epidemic is also correlated with the intensification of Douglas-fir plantation management from the 1960's to 1990's, and the conversion of mixed western hemlock, Douglas-fir, Sitka spruce, red alder, and western redcedar stands to young monocultures of Douglas-fir [1]. Fertilization appears to have no effect on disease severity [27]. Although there have been no published accounts, it appears that disease is not as severe within old-growth Douglas-fir crowns, perhaps due to vertical diversity of microclimate and foliage nutrition.

In general, winter temperature has been steadily increasing with the mean annual temperature in the Pacific Northwest (PNW), which has increased 0.2 °C per decade [28]. Spring and summer precipitation has been increasing approximately 2%–3% per decade [28]. These linear changes in winter temperature and spring precipitation are consistent with the epidemiology factors that increase disease pressure. Recently, Lee et al. [29] investigated impacts of SNC on Douglas-fir growth at several Cascade Mountains sites using dendrochronological techniques. They contend that SNC impacts are present and measureable at these sites, but that climate influences are distinct from coastal sites, and that winter temperature is much more important. This implies that SNC disease severity varies on the landscape in a complex way and each geographical location has unique environmental controls on disease.

In the western Oregon Cascade Range, there was no apparent effect of SNC on Douglas-fir growth from 2001 to 2011 in the stands sampled. SNC levels from 2001–2011 in the western Cascade Range were not as severe as in the Oregon Coast Range. Only a few stands sampled in the Cascades had mean foliage retention of <3 years. There were no stands with mean stomatal occlusion densities >50% on 2-year-old needles in 2001, 2006, and 2011. Oregon Cascade Range site characteristics, including plant associations, soil chemistry and parent material, air temperatures, and monthly precipitation and leaf wetness, may not be as conducive to elevated populations of the causal fungus, *P. gaeumannii*, and subsequent severe defoliation, as in the Coast Range.

Management of Swiss needle cast in Douglas-fir plantations of western Oregon involves a nuanced approach that varies with geographical and environmental setting and has been summarized by Shaw et al. [3], Jayawickrama et al. [30], Mulvey et al. [31] and Zhao et al. [32] based on works of many researchers and the Swiss Needle Cast Cooperative at Oregon State University. Standard silvicultural treatments commonly applied in the Douglas-fir region do not appear to increase or decrease disease severity [3,33] and fungicides are not recommended for economic and environmental reasons. Therefore, an integrated pest management (IPM) strategy based on a non-chemical approach is suggested for this foliage disease.

Landowners should determine their economic/growth threshold for change from traditional Douglas-fir silvicultural prescriptions. This assessment depends on the age and composition/density of the individual stand. With an estimate of needle retention, either from a field estimate or one of the aforementioned models, average growth losses can be estimated from published research [2]. For assessment of individual stands, the SNCC has developed a stand assessment tool, enabling comparison of the growth of measured trees to that predicted for the same trees with a regional growth model, assuming no SNC [5]. Traditional tree improvement programs hold promise for improving tolerance of disease under moderate and lower disease severity [30]. Under high disease severity, alternative species are recommended [34], such as western hemlock, western redcedar, Sitka spruce, or red alder, though these species have specialized management requirements and generally have less value in the current log market. Management of western hemlock alone or with mixes of Douglas-fir have been suggested across the gradient of disease severity and to take advantage of natural regeneration among the planted Douglas-fir. Zhao et al. [32] recommend precommercial thinning selection of both species, depending on their relative size.

The Swiss Needle Cast Cooperative (Oregon State University, Oregon Department of Forestry, US Forest Service, Bureau of Land Management, Stimson Lumber, Starker Forests, and Weyerhaeuser Corp) and private forest landowner partners are facilitating long term monitoring using aerial detection and ground survey based growth impact and disease severity monitoring plots. These monitoring techniques are necessary to understand the continuing dynamics of disease on the landscape and develop IPM strategies based on known impacts to tree growth. Silvicultural experimentation and alternative/mixed species management, combined with tree improvement and continued epidemiology and silvicultural research will aid management of this on-going disease epidemic.

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Abbreviations

The following abbreviations are used in this manuscript:

SNCC	Swiss Needle Cast Cooperative
SNC	Swiss needle cast
PNW	Pacific Northwest

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