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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.

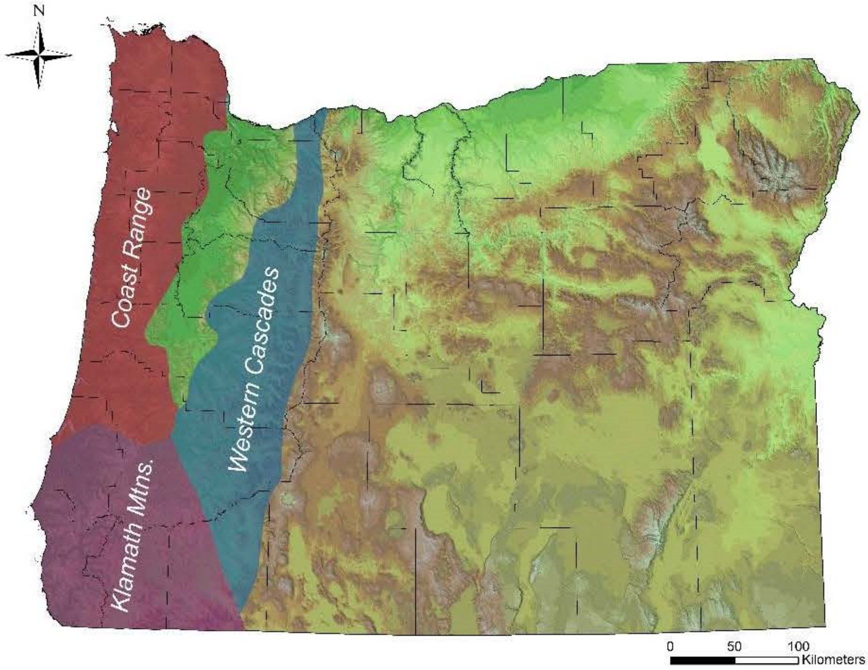

Figure 1. Mountain ranges of western Oregon, USA.

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).

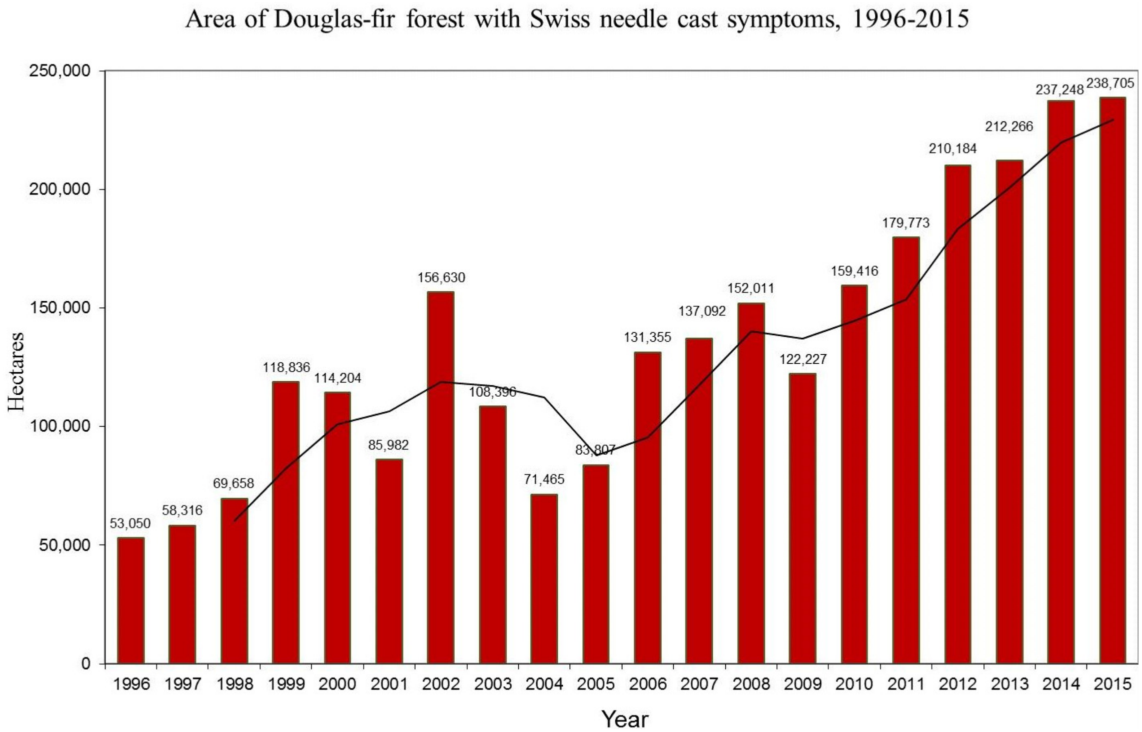

Figure 4. Area of Douglas-fir forests with Swiss needle cast symptoms determined from aerial survey in late spring from 1996 to 2015 (20 years).

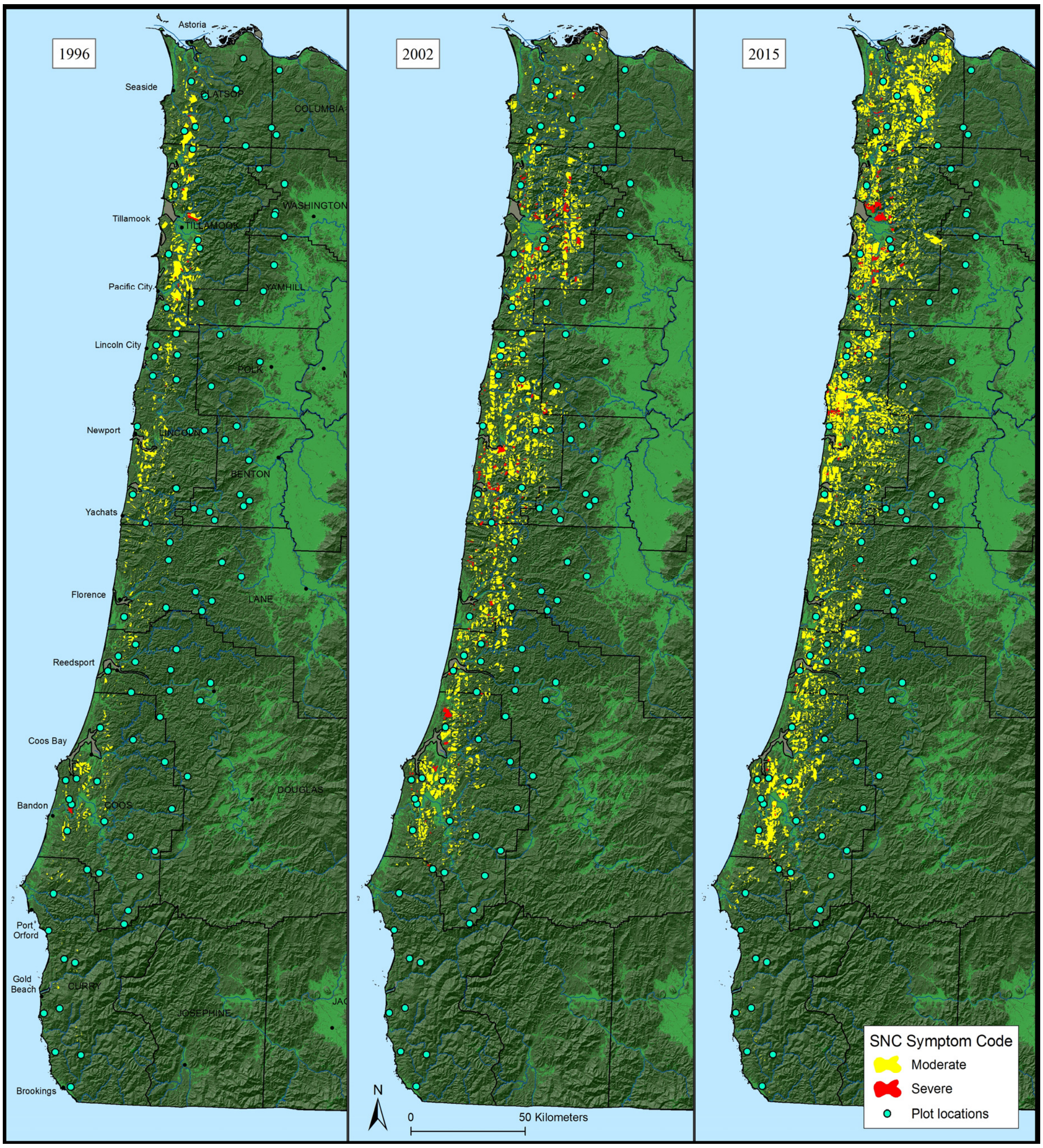

Figure 5. Spatial pattern of Swiss needle cast-symptomatic Douglas-fir in the Coast Range of Oregon as determined by aerial detection survey in 1996, 2002, and 2015. Yellow indicates moderate symptoms, while red indicates severe symptoms. The blue dots represent new plot network.

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.

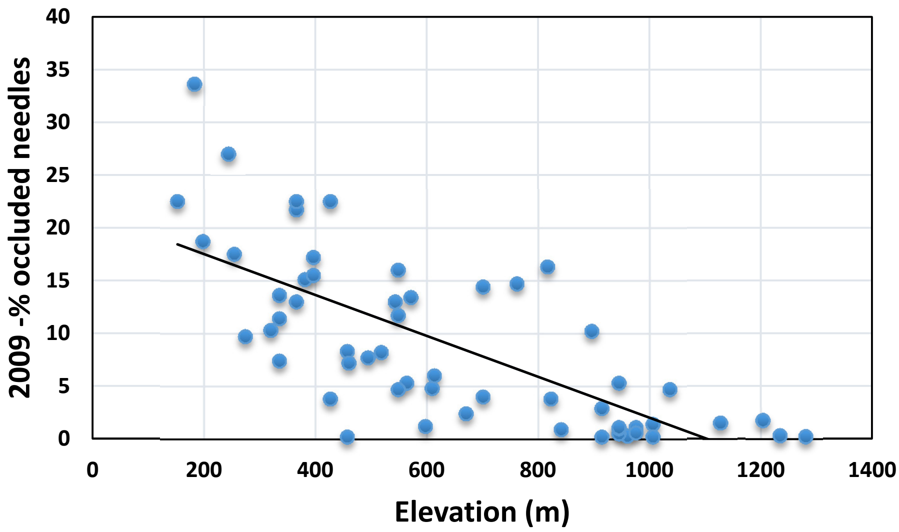

Figure 6. 2009 (2-year-old) needle-pseudothecial density vs. elevation. $R^2 = 0.54$, $p < 0.0001$.

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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Conflicts of Interest: The authors declare no conflict of interest.

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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