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Thinning Mixed-Species Stands of Douglas-Fir and Western Hemlock in the Presence of Swiss Needle Cast: Guidelines Based on Relative Basal Area Growth of Individual Trees

Junhui Zhao, Douglas A. Maguire, Douglas Mainwaring, Jon Wehage, and Alan Kanaskie

In coastal forests of the Pacific Northwest, young coniferous plantations typically contain a mixture of planted and natural Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). Swiss needle cast (SNC) disease inhibits the growth of Douglas-fir to varying degrees in these stands, depending on SNC severity. In addition to the value differential between Douglas-fir and western hemlock, foresters must account for differences in growth potential (tree size, competitive position, site characteristics, disease pressure) when selecting trees for retention during thinning operations. Diameter increment models for Douglas-fir and western hemlock were developed from permanent plot data collected for the SNC growth impact study (GIS), precommercial thinning study (PCT), commercial thinning study (CT), and retrospective commercial thinning study (RCT). Predictor variables represent tree size, competitive position, site characteristics, and SNC severity. SNC severity was indexed by foliage retention, defined as the number of annual needle cohorts held by a tree. Foliage retention was positively correlated with Douglas-fir diameter increment and negatively correlated with western hemlock diameter increment. Charts developed from the diameter growth models provide a field tool for assessing the relative basal area growth of adjacent Douglas-fir and western hemlock of a given initial diameter in a stand of given SNC severity. In a stand with severe SNC (foliage retention = 1.5 years) the basal area growth of a 6-in. western hemlock tree will exceed the basal area growth of any Douglas-fir tree up to 7.7 in. in DBH. In a relatively healthy stand (foliage retention = 3.0 years) the basal area growth of 6 in. Douglas-fir and western hemlock trees will be approximately equivalent.

Keywords: relative growth, basal area increment, foliage retention, disease severity, thinning guidelines

Young Douglas-fir plantations (≤40 years) are tremendously important to the economic and environmental health of Oregon and Washington due to their extent and productivity (Campbell et al. 2004, Gray et al. 2005). Over the past 20 years, coastal forests in this region have been suffering from an epidemic of Swiss needle cast (SNC), a foliar disease of Douglas-fir (*Pseudotsuga menziesii*) caused by the Ascomycete *Phaeocryptopus gaeumannii* (Hansen et al. 2000). Productivity of Douglas-fir in affected stands has diminished considerably, with volume growth losses reaching as high as 50% due to premature needle abscission and disruption of photosynthesis in surviving foliage (Hansen et al. 2000, Manter et al. 2003, 2005, Maguire et al. 2011). Annual aerial surveys of three million acres of coastal forests conducted by the Oregon Department of Forestry indicate that the area of symptomatic forest (stands with visible chlorosis) has been fluctuating annually but has also been gradually increasing since 1996. The SNC-affected area reported in 2012 was 519,375 ac, the highest total since the aerial survey began (Kanaskie and McWilliams 2013). The extent of discoloration is particularly significant given the relatively aggressive conversion of both merchantable and nonmerchantable Douglas-fir stands to nonsusceptible tree species in the most severely impacted areas.

Precommercial thinning is commonly used to achieve management objectives in stands where high stand density limits individual tree growth and reduces vigor to a level that leaves trees more susceptible to insects and disease (Mitchell et al. 1983). Precommercial thinning was among the earliest silvicultural treatments applied in severely SNC-impacted stands to test for possible beneficial or detrimental effects on residual tree growth and foliage retention (Kanaskie et al. 1998). Results from a commercial thinning study

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Affiliations: *Junhui Zhao (junhui.zhao@oregonstate.edu), Oregon State University, Corvallis, OR. Douglas A. Maguire (doug.maguire@oregonstate.edu), Oregon State University. Douglas Mainwaring (doug.mainwaring@oregonstate.edu), Oregon State University. Jon Wehage, Stimson Lumber Company, Tillamook, OR. Alan Kanaskie, Oregon Department of Forestry, Salem, OR.* *This project was funded by the Swiss Needle Cast Cooperative hosted at Oregon State University.*

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indicate that infected stands respond positively to thinning (Mainwaring et al. 2005a, n.d.). However, consistent with unthinned stands (Maguire et al. 2011), Douglas-fir growth in precommercial thinning stands remains lower than its potential in absence of SNC. With continued increase in affected area of coastal Douglas-fir, land managers are not currently emphasizing Douglas-fir as much as they have in the recent past in coastal Oregon. Specifically, silvicultural strategies have shifted to interplanting with nonsusceptible species and preferential retention of the both planted and naturally regenerated trees of these other species during precommercial thinning.

The SNC problem is mostly limited to the strip of land between the Pacific Ocean and approximately 20 miles inland, with the disease gradually diminishing in intensity from west to east, probably due to climate factors strongly influenced by proximity to the Pacific Coast (Zhao et al. 2011). Natural stands within the narrow *Picea sitchensis* vegetation zone immediately adjacent to the ocean (Franklin and Dryness 1973) have historically contained a mixture of other commercial species, including western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), and red alder (*Alnus rubra*), with much less Douglas-fir than is currently present. Within this zone, conversion of naturally regenerated stands to Douglas-fir plantations during the 1970s is believed to have played a role in the elevation of SNC from endemic to epidemic status (Hansen et al. 2000), but many other climatic and nutritional factors are probably contributing to the emergence of SNC as a serious obstacle to growing Douglas-fir in this coastal band (El-Hajj et al. 2004, Manter et al. 2005, Stone et al. 2008, Zhao et al. 2011).

Due to its historically greater value, Douglas-fir continues to be an important component of planted stands. Increasing proportions of Douglas-fir are generally planted from west to east within the coast ranges of Oregon, with western hemlock most commonly planted as the substitute species (Beth Fitch, pers. comm.). Natural regeneration of western hemlock contributes to this planned shift in species composition with closer proximity to the coast, presumably due to higher precipitation and lower summer temperatures (Schrader 1998). The abundance of natural regeneration of hemlock generally increases along the gradient of increasing SNC severity in Douglas-fir. Although prolific natural regeneration often makes density control in these stands necessary, the resulting mix of Douglas-fir and hemlock also provides an opportunity for manipulating species composition to match the anticipated relative growth performance of the two species at any one location.

In the absence of SNC, a larger planted Douglas-fir would be retained during thinning in preference to a smaller western hemlock, given the equal or greater growth potential of Douglas-fir and its higher market value. However, the current negative growth impact of SNC should be accounted for in determining the best species mix for coastal stands. With appropriate diameter increment equations, expected relative growth rates of the two species can be assessed by considering SNC intensity, stand structure, site quality, and relative size.

Individual-tree diameter increment models are routinely applied to simulate the growth dynamics among trees in stands of varying structure and among sites of varying quality (Wykoff 1990, Monserud and Sterba 1996, Trasobares et al. 2004). Diameter or basal area growth is fundamental to these growth models (Cao 2000, Westfall 2006), in part because it is a dimension that is relatively easy to measure with high precision and in part because it is widely used for predicting future tree volume or biomass, as well as probability of survival (Yang et al. 2009). In many models, diameter growth is expressed as a function of tree size, competition effects, and site characteristics (Wykoff 1990, Hann and Hanus 2002, Trasobares and Pukkala 2004, Zhao et al. 2004, Calama and Montero 2005, Uzoh and Oliver 2008, Hartmann et al. 2009). Previous work makes it clear that a distance-independent, individual-tree model structure is flexible enough to predict diameter growth in pure even-aged stands as well as in mixed multiaged stands (Monserud and Sterba 1996, Lhotka and Loewenstein 2011).

The aims of the present study were: (1) to develop distance-independent individual-tree diameter growth models for young Douglas-fir and western hemlock trees growing in mixed-species stands across a gradient in SNC severity; (2) to compute the implied relative basal area growth of Douglas-fir and western hemlock trees of varying initial diameter as a function of foliage retention; and (3) to develop a field chart to help managers select trees for removal and retention during thinning of mixed Douglas-fir and hemlock stands.

Methods

Field Sites

Data for this analysis were compiled from four ongoing studies established on predominately Douglas-fir sites to investigate the influence of SNC on growth losses and response to thinning (Table 1). Plots were established across a range in topographic positions and SNC severity. Latitudes ranged from 43.5°N to 46.22°N, longitudes from 124.06°W to 122.29°W, and elevation from 45 to 1,024 feet (ft) above sea level (Figure 1). Over the last 40 years, the mean January minimum for this region was 32 °F and the mean July maximum was 77 °F. Total annual precipitation averaged 59–118 in., with approximately 70% of the total falling from October to March.

The growth impact study (GIS) was established in the winter and spring of 1998 within 76 Douglas-fir plantations ranging in total age from 10 to 30 years. These plots were established to monitor SNC severity and growth impacts within young stands in the Oregon Coast Range (Maguire et al. 2002, 2011). These plantations were sampled from a population of stands located within 18 miles of the Pacific coast and between the cities of Newport in the south and Astoria in the north.

The precommercial thinning study (PCT) was established in 23 Douglas-fir plantations to assess the effects of precommercial thinning on SNC symptom development and possible growth reduction (Kanaskie et al. 1998). In April and May of 1998, 23 paired plots were established within 29 miles of the Pacific coast and between the cities of Newport and Astoria. One plot in each pair was precommercially thinned to approximately 200 trees per acre in May 1998 (because of initial stocking levels, at two sites the target residual was 100 trees per acre). At five of the 23 locations, an additional plot was thinned to approximately 100 trees per acre. Only the unthinned stands were used in the present study.

The commercial thinning study (CT) was established in 30 stands scheduled for commercial thinning. These stands were older, ranging from 25 to 60 years, and were sampled to test the influence of commercial thinning on tree growth and SNC symptom development (Mainwaring et al. 2004, 2005b). Half of the plots were established prior to the 2002 growing season while the other half were established prior to the 2003 growing season. Prior to thinning, paired 0.5-ac fixed area plots, each with a 33-ft. buffer, were established in each stand. One of the plots was thinned while the other was left unthinned. Plots were chosen to fill a sampling matrix

Table 1. Summary of stand characteristics in Swiss Needle Cast Cooperative database for modeling individual-tree diameter growth of Douglas-fir and western hemlock in the Oregon Coast Ranges.

Species	Variable	Mean	Std dev	Min	Max	Mean	Std dev	Min	Max
		Modeling data set (383 plots)				Validation data set (92 plots)			
Douglas-fir	**Age (yr)**	27.34	12.31	8.00	75.78	25.57	10.99	12.00	66.51
	FR (yr)	2.50	0.66	1.10	4.63	2.39	0.54	1.01	4.09
	Distance (mile)	14.07	11.39	0.60	87.60	12.49	9.78	0.60	78.20
	BA (ft^2/ac)	125.95	52.68	17.20	344.67	121.17	48.90	7.44	256.75
	CCF (ft^2/ac)	184.28	72.36	38.00	553.54	177.56	57.02	38.97	305.02
	D40 (in.)	12.23	3.85	3.39	25.59	11.82	3.76	2.19	20.75
	H40 (ft)	65.11	25.41	18.25	157.49	61.21	24.03	13.17	133.63
	TPA (trees/ac)	434.22	301.22	42.00	2099.11	417.54	234.64	72.00	1,094.53
	QMD (in.)	8.56	3.83	2.54	22.70	8.21	3.42	1.62	18.25
	SDI (in.)	249.66	97.88	52.22	783.29	240.70	82.55	28.01	443.96
	SI (ft)	139.78	20.60	46.92	205.05	141.06	23.27	45.28	207.02
Western hemlock		Modeling data set (181 plots)				Validation data set (42 plots)			
	Age (yr)	28.07	12.80	11.00	75.78	26.29	12.54	13.00	66.51
	FR (yr)	2.36	0.67	1.10	4.63	2.37	0.44	1.48	3.30
	Distance (mile)	12.68	13.78	0.60	87.60	10.57	12.59	0.60	78.20
	BA (ft^2/ac)	138.81	54.68	25.30	344.67	132.00	49.94	16.24	256.75
	CCF (ft^2/ac)	203.49	78.77	62.89	553.54	191.18	52.57	43.16	304.58
	D40 (in.)	12.39	3.72	4.23	23.71	12.03	3.68	4.88	20.75
	H40 (ft)	65.16	24.82	20.75	156.39	60.50	24.57	27.74	133.55
	TPA (trees/ac)	515.59	343.54	42.00	2099.11	481.89	238.45	72.00	1,094.53
	QMD (in.)	8.24	3.63	2.89	22.70	7.81	3.21	3.26	18.25
	SDI (in.)	281.09	107.75	75.73	783.29	266.98	83.23	46.35	443.94
	SI (ft)	136.97	20.50	86.61	198.16	142.55	21.77	104.00	207.02

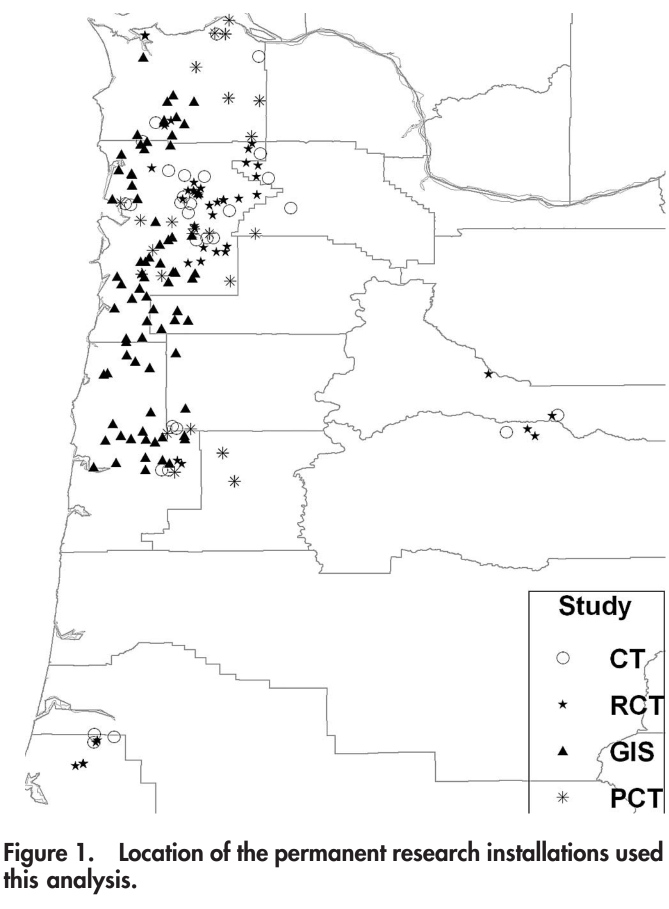

Figure 1. Location of the permanent research installations used in this analysis.

based on three levels of SNC severity (severe, moderate, light) and two levels of Douglas-fir stand density (relative density 20–35 and 35–50 ft^2·ac^{-1}·in$^{-0.5}$; Curtis 1982). Located on state land managed by the Oregon Department of Forestry, 28 of the stands were in the Oregon Coast Ranges and two were in the western foothills of the Cascade Mountains. Only the unthinned plots were used in this analysis.

The retrospective commercial thinning study (RCT) was established in 40 Douglas-fir stands that were 30- to 60-years-old and had been commercially thinned 4–10 years prior to plot establishment in 2002. This study was initiated to study the effects of commercial thinning on retrospective stand development under varying levels of current SNC (Mainwaring et al. 2005a).

Plot and Tree Measurements

In the younger GIS and PCT plantations, all trees with diameter at breast height (DBH) ≥2 in. (5 cm) were tagged on 0.2 ac (0.08 ha) permanent plots established in 1998. Trees were remeasured in 2000, 2002, 2004, and 2008. DBH was recorded for all trees, and total height (HT) and height to lowest live branch (HLB) were measured on a subsample of Douglas-fir trees across the diameter range. Where small trees (DBH < 2 in.) were abundant, a 0.05 ac (0.02 ha) subplot was established and only these small trees were measured for DBH on this nested subplot. Ten dominant or codominant trees were scored annually in April or May for SNC severity. On each tree, crown length was divided into thirds and foliage retention (FR) estimated visually as the average number of annual needle cohorts. Tree-level foliage retention was computed as the average of all crown thirds and plot-level retention as the average of all 10 sample trees.

In the CT stands, all trees with DBH ≥ 2 in. (5 cm) were tagged on square 0.5 ac (0.2 ha) permanent plots established during the winter prior to the 2002 or 2003 growing seasons. Trees were measured before the growing season of 2002, 2004, and 2006 on the 15 plots established in 2002 and before the growing seasons of 2003, 2005, and 2007 for the 15 plots established in 2003. All tagged trees were measured for DBH and a subsample of 40 Douglas-fir trees was measured for HT and HLB. This subsample included the 10 largest Douglas-fir trees by DBH and the four smallest by DBH, with the remaining 26 distributed evenly across the DBH range within the

Table 2. Summary of tree characteristics in Swiss Needle Cast Cooperative database for modeling individual-tree diameter growth of Douglas-fir and western hemlock in the Oregon Coast Ranges.

Species	Variable	Mean	Std dev	Min	Max	Mean	Std dev	Min	Max
		Modeling data set (23,510 trees)				Validation data set (5,763 trees)			
Douglas-fir	**DBH (in.)**	9.10	4.30	0.12	39.09	8.75	4.05	0.04	38.39
	CR	0.70	0.18	0.07	1.00	0.72	0.17	0.03	1.00
	BAL (ft^2/ac)	77.05	50.82	0.00	331.03	75.92	51.34	0.00	248.93
	CCFL (ft^2/ac)	97.97	63.87	0.00	516.79	97.78	61.60	0.00	304.39
	ΔDBH (in./year)	0.24	0.18	0.00	1.32	0.25	0.18	0.00	1.14
Western hemlock		Modeling data set (4,219 trees)				Validation data set (576 trees)			
	DBH (in.)	6.13	3.70	1.93	40.71	6.43	3.71	2.24	21.85
	CR	0.81	0.14	0.19	1.00	0.84	0.11	0.23	1.00
	BAL (ft^2/ac)	120.62	75.85	0.00	340.94	106.44	64.76	0.00	256.68
	CCFL (ft^2/ac)	170.75	115.31	0.00	534.76	135.04	72.97	0.00	276.04
	ΔDBH (in./year)	0.27	0.21	0.00	1.26	0.33	0.23	0.00	1.20

plot. On the largest 10 Douglas-fir trees, breast height ages were also obtained by coring the trees. Due to the height of crowns and associated visibility problems in these older, larger trees, binoculars were used to estimate a single foliage retention on the 5–10 largest trees on each plot.

In the RCT stands, all trees with DBH $\geq$ 2 in. (5 cm) were tagged and measured on square 0.5 ac (0.2 ha) permanent plots established during the winter of 2001–2002. The plots were remeasured just before the growing seasons of 2005 and 2006, and individual tree measurements (DBH, HT, HLB, and foliage retention) were measured the same way as on the CT plots. Breast-height ages were obtained from the 10 largest Douglas-fir trees and foliage retention on the same 10 trees provided an estimate of SNC severity.

Model Development

Periodic annual increment in tree diameter was modeled as a function of tree size, competitive position, site attributes and SNC severity. The tested explanatory variables include the following:

1. Tree size variables: DBH, in addition to its logarithmic, inverse, and squared transformations.

2. Competition variables: number of stems, TPA (stems/ac); average diameter of largest 40 trees by DBH, D40 (in.); average height of largest 40 trees by DBH, H40 (ft); quadratic mean diameter of all trees, QMD (in.); stand age, Age (year); total basal area, BA (ft^2/ac); crown competition factor, CCF (Krajicek et al. 1961); stand density index, SDI; basal area of trees larger than the subject tree, BAL (ft^2/ac); crown competition factor in trees larger than the subject tree (CCFL); and various transformations of these variables. Crown competition factor (CCF, Krajicek et al. 1961) was calculated for each plot and inventory year with species-specific maximum crown width estimated from equations developed by Paine and Hann (1982) and Bechtold (2004). Reineke's (1933) SDI was computed as the competitive equivalent of a varying number of trees per acre with a quadratic mean diameter of 10 in.

3. Site characteristics: Bruce's site index (Bruce 1981), SI (ft) and distance from coast, DIST (miles), in addition to their squared, logarithmic, and inverse transformations.

4. SNC severity: the number of years of retained foliage, FR, along with its squared, logarithmic, and inverse transformations.

Various linear and nonlinear models were fitted to the data to model periodic annual diameter growth of Douglas-fir and western hemlock. Linear diameter increment models with the logarithm of diameter growth as the response variable were tested in the first stage of model fitting. Potential predictor variables at the tree level and stand level were selected based on the available data and their biological significance to tree growth (Wykoff 1990, Zhao et al. 2004). A combination of methods was used to select the variables and their transformations: (1) stepwise regression; (2) subjective selection based on known drivers of stand dynamics (tree size, competition, site characteristics, and SNC severity); and (3) selection based on a combination of statistical fit and biological interpretability. The linear model was estimated using the maximum likelihood procedures in PROC REG in SAS version 9.2 (SAS Institute, Inc. 2008).

At the second stage, nonlinear diameter increment models were tested using the predictors identified with the log-linear diameter increment models. The nonlinear model was estimated using maximum likelihood by PROC NLIN in SAS version 9.2 (SAS Institute, Inc. 2008). Preliminary analysis indicated that a random plot effect was not suitable in accounting for the repeated measurements across different growth periods, primarily because the random plot effect served in part as a surrogate for plot-level foliage retention. Final models were chosen on the basis of statistical significance of parameter estimates (α = 0.05), residual analysis, and biological interpretability.

For selecting the most suitable regression model, it is generally advisable to use some measure of lack of fit in combination with one or more test statistics (Kozak and Kozak 2003). An independent dataset can provide validation of model accuracy (Kariuki 2008). In this study, a random selection of 80% of the data was used for initial model development, and the remaining 20% was set aside to evaluate growth model accuracy (Table 2). The models were evaluated quantitatively by examining the magnitude and distribution of residuals on all possible combinations of variables to detect any obvious dependencies or patterns that indicate systematic bias. A fit index (FI) was computed as an analog to R^2, in addition to root mean square error (RMSE), mean bias (MB), and absolute mean bias (ABS)

$$FI = 1 - \frac{\sum_{i=0}^{n}(\Delta \mathrm{DBH} - \widehat{\Delta \mathrm{DBH}})^2}{\sum_{i=0}^{n}(\Delta \mathrm{DBH} - \overline{\Delta \mathrm{DBH}})^2} \quad (1)$$

$$RMSE = \frac{1}{n}\sum_{i=0}^{n}(\Delta \mathrm{DBH} - \Delta\widehat{\mathrm{DBH}})^2 \quad (2)$$

$$MB = \frac{1}{n}\sum_{i=0}^{n}(\Delta \mathrm{DBH} - \Delta\widehat{\mathrm{DBH}}) \quad (3)$$

$$AMB = \frac{1}{n}\sum_{i=0}^{n}(|\Delta \mathrm{DBH} - \Delta\widehat{\mathrm{DBH}}|) \quad (4)$$

Here n was the number of observations; ΔDBH was the measured diameter increment; $\Delta\widehat{\mathrm{DBH}}$ was predicted diameter increment; and $\Delta\overline{\mathrm{DBH}}$ was mean measured diameter increment.

Trends in diameter growth implied by the fitted models over initial tree diameter and SNC intensity were graphically assessed for their behavior by setting other predictor variables to their averages across the entire dataset.

Thinning Guidelines

To illustrate potential application of the models, implied basal area growth was computed assuming that a subject stand had 400 trees/ac (988 trees/ha), including 250 Douglas-fir/ac (618 trees/ha) and 150 western hemlock/ac (370 trees/ha). Western hemlock trees ranged in diameter from 2 to 12 in. (5.1 to 30.5 cm), and Douglas-fir trees ranged in diameter from 0 to 5 in. (0 to 12.7 cm) larger than the western hemlock. For simplicity, all Douglas-fir trees were assumed to have equal DBH and all western hemlock trees were likewise assumed to have equal diameters, but 0 to 5 in. (0 to 12.7 cm) smaller than Douglas-fir. Plantation age was set to 10 years. The ratio of basal area growth of the Douglas-fir and western hemlock trees was computed as a function of foliage retention and the difference between the diameters of the two species. This basal area growth ratio was plotted on the diameter difference between the two species for different SNC intensities as measured by foliage retention. For a given foliage retention, the diameter difference between the two species at which the growth ratio equals one (or some other value of the forester's choice) implies a diameter difference threshold that can be applied during a thinning to select the leave tree from a pair of adjacent trees of the two species.

Results

A large range of tree sizes was available for both species, with Douglas-fir exhibiting a greater diameter range (Table 2). The following final diameter increment equation for Douglas-fir included variables representing initial tree size, competition, and SNC severity

$$\Delta \mathrm{DBH} = \exp(\alpha_0 + \alpha_1 \times \mathrm{DBH} + \alpha_2 \times \mathrm{DBH}^2 + \alpha_3 \times \log(\mathrm{Age}) + \alpha_4 \times \frac{\mathrm{BAL}^2}{\mathrm{DBH}} + \alpha_5/\mathrm{FR} + \alpha_6 \times \mathrm{H40} + \alpha_7 \times \log(\mathrm{BA})) + \varepsilon_1 \quad (5)$$

where ΔDBH = Periodic annual diameter growth of a Douglas-fir (in./year)

DBH = initial tree diameter (in.)

Age = plantation age (year)

Table 3. Parameter estimates and their standard errors for the Douglas-fir and western hemlock diameter growth models (Equations 5 and 6).

		Douglas-fir		Western hemlock	
Parameter	Variable	Estimate	Standard error	Estimate	Standard error
α_0	Intercept	1.8601	0.0423		
α_1	DBH	0.1297	0.0033		
α_2	DBH^2	−0.0026	0.0001		
α_3	Log(Age)	−0.3702	0.0149		
α_4	BAL^2/DBH	−0.0003	0.0000		
α_5	1/FR	−1.0002	0.0270		
α_6	H40	−0.0092	0.0004		
α_7	Log(BA)	−0.3769	0.0080		
β_0	Intercept			−0.8082	0.0958
β_1	Log(DBH)			0.8632	0.0313
β_2	DBH^2			−0.0006	0.0001
β_3	Log(Age)			0.2710	0.0442
β_4	BAL^2/DBH			−0.0001	0.0000
β_5	1/FR			0.8242	0.0407
β_6	H40			−0.0245	0.0010
β_7	Log(BA)			−0.3461	0.0150

BAL = basal area in trees with larger DBH than subject tree (ft^2/ac)

FR = plot mean foliage retention (years)

H40 = average height of largest 40 trees by DBH (ft)

BA = total basal area per acre (ft^2/ac)

α_k = parameter to be estimated from the data

ε_1 = random error with $\varepsilon \sim N(0,\sigma_1{}^2)$

All parameter estimates for Douglas-fir (Table 3) were significantly different from zero at α=0.05, the fit index was 0.6177, RMSE was 0.0875, MB was 0.0011, and AMB was 0.0831. Residual plots indicated that the model provided a good fit to the data. Validation using 20% of the plots produced a fit index of 0.5871, RMSE of 0.1147, MB of 0.0028, AMB of 0.0858.

The following final model describing western hemlock diameter increment also included variables representing tree size, competition, and SNC severity

$$\Delta \mathrm{DBH} = \exp(\beta_0 + \beta_1 \times \log(\mathrm{DBH}) + \beta \times \mathrm{DBH}^2 + \beta_3 \times \log(\mathrm{Age}) + \beta_4 \times \frac{\mathrm{BAL}^2}{\mathrm{DBH}} + \beta_5/\mathrm{FR} + \beta_6 \times \mathrm{H40} + \beta_7 \times \log(\mathrm{BA})) + \varepsilon_2 \quad (6)$$

where ΔDBH = Periodic annual diameter growth of a western hemlock (in./year); β_k = parameter to be estimated from the data

ε_2 = random error with $\varepsilon \sim N(0,\sigma_2{}^2)$

and all other variables were defined above.

All parameter estimates for western hemlock (Table 3) were significantly different from zero at α=0.05, the fit index was 0.6243, RMSE was 0.1014, MB was −0.0010, and AMB was 0.0954. Residual plots indicated that the model provided a good fit to the data. Validation using 20% plots produce fit index of 0.6470, RMSE of 0.1349, MB of 0.0409, AMB of 0.1033.

SNC severity was negatively correlated with Douglas-fir diameter increment but positively correlated with western hemlock diameter increment. Douglas-fir diameter increment under severe SNC (foliage retention of 1.5 years) was only 69% of that expected in a comparable uninfected stand (foliage retention of 3.5 years) (Figure

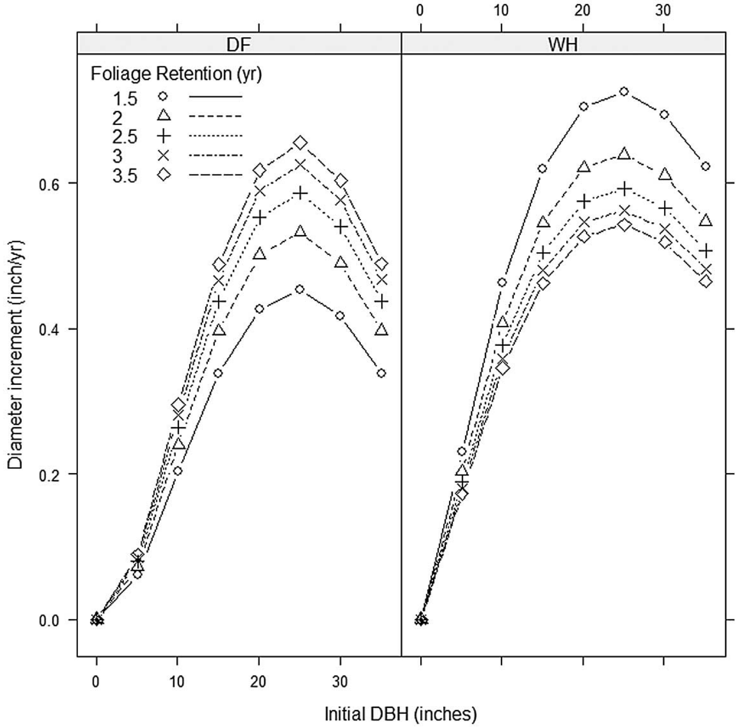

Figure 2. Diameter increment of Douglas-fir and western hemlock for a given initial diameter and SNC severity (foliage retention) in a stand with average age, QMD, TPA, H40, and BA. BAL for Douglas-fir and western hemlock was calculated from BA, DBH, QMD, and H40. Specifically, for Douglas-fir, BAL = −4.88468 + 0.61475*BA − 13.85379*DBH + 9.36785*QMD + 0.35728*H40 + 12.11854*log(DBH), (R^2 = 0.8448); for western hemlock, BAL = 59.14009 + 0.66528*BA − 5.12461*DBH + 6.64968*QMD + 0.50032*H40 − 56.16876*log(DBH) (R^2 = 0.8149).

Table 4. Parameter estimates and their standard errors for the relationship between mean diameter and mean height of the 40 largest (by diameter) trees per acre in the SNCC database (Equation 7).

Parameter	Estimate	Standard Error
γ_1	224.9	6.9582
γ_2	−16.814	0.4839
γ_3	10.1474	2.5272

2). In contrast, western hemlock growing in the same mixed-species stand grew 34% more in diameter where foliage retention in Douglas-fir was only 1 year.

As indicated in the methods sections, the graphs constructed for depicting the basal area growth ratios as a function of initial tree diameter and foliage retention relied on some assumptions that simplified the wide range in possible stand structures (specifically the diameter and height distributions by species). These assumptions allowed an approximate assessment of relative basal area growth of Douglas-fir and western hemlock trees in stands with two potential components: a set of Douglas-fir with uniform diameters and heights and a set of western hemlock with uniform diameters (and implied equal heights) that were less than or equal to the diameter of the Douglas-fir component. When constructing the field charts, compatibility between DBH and H40 was ensured by fitting the following equation to the dataset (Table 4)

$$H40 = 4.5 + \gamma_1 * exp(\gamma_2 / D40 + \gamma_3 / BA) + \varepsilon_3 \qquad (7)$$

where γ_k=parameter to be estimated from the data
ε_3=random error with $\varepsilon \sim N(0,\sigma_3{}^2)$

Fit index of the above model was 0.8029, and RMSE was 11.19.

The Douglas-fir and western hemlock diameter growth models implied that, as SNC severity increased, successively smaller western hemlock trees are capable of matching or exceeding the basal area growth of Douglas-fir (Figure 3). Under the assumptions made to generate the charts (Figure 3), basal area growth of individual Douglas-fir trees in a healthy stand (foliage retention of about 3.5 years) would always exceed that of western hemlock. Basal area growth ratio between western hemlock and Douglas-fir trees increasing with increasing SNC severity (declining foliage retention). Western hemlock trees with DBH of 2–10 in. can outgrow Douglas-fir of the same size if SNC is sufficiently severe. For western hemlock with DBH larger than 12 in., basal area growth of an equal or larger Douglas-fir would always be greater, regardless of SNC intensity. In stands with severe SNC, (foliage retention of 1.5 years or less), basal area growth of individual western hemlock trees with DBH of approximately 4–6 in. exceeds that of Douglas-fir trees that are up to 2 in. greater in DBH (Figure 3).

Discussion

In the last 20 years, SNC has emerged as sufficiently influential in the Oregon Coast Ranges that land managers can no longer plant or tend Douglas-fir without considering SNC effects on Douglas-fir growth, on its ability to compete against other species, and even on survival of Douglas-fir to commercial size. Although it has been estimated that Douglas-fir remained financially competitive with other local conifer species even with as much as a 50% volume growth loss (Elwood and Mainwaring 2004), this conclusion relies on assumptions about relative value. Furthermore, knowledge that

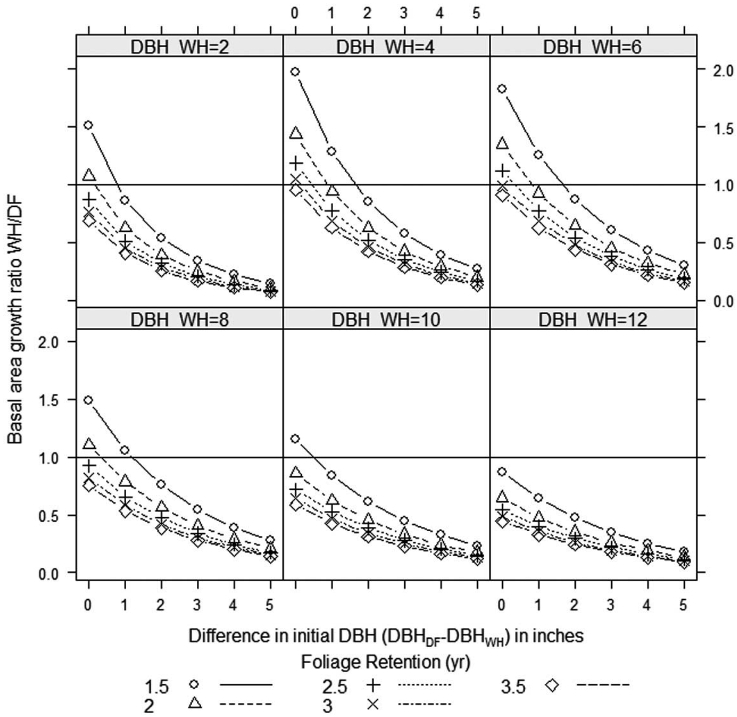

Figure 3. Ratio of western hemlock to Douglas-fir basal area growth as a function of size differential (DBH_{DF}-DBH_{WH}) between Douglas-fir and western hemlock under different initial diameters of western hemlock (DBH_WH) and SNC severity (foliage retention). Assumptions required to construct these charts were described in the methods section. H40 was calculated using Equation 7 to ensure compatibility with DBH.

SNC is at least influenced if not controlled by climate factors (Manter et al. 2005, Zhao et al. 2011), coupled with anticipated changes in future Pacific Northwest climates, suggests that the current epidemic may not just be a short-term anomaly (Stone et al. 2008). Although research has identified Douglas-fir families that exhibit tolerance to SNC (Johnson 2002, Temel et al. 2005), the enhanced performance of such families are believed to be practical only in areas of moderate infection, not where disease intensity is high (Filip et al. 2000). Managers must consider including greater proportions of nonsusceptible species on forestland within areas of higher SNC risk (Filip et al. 2000).

Western hemlock generally has slower juvenile height growth than Douglas-fir, but its shade tolerance allows it to persist in stands where the two species are associated (Tesch 1995). In healthy even-aged stands, growth rates of the two species tend to diverge as western hemlock becomes overtopped by Douglas-fir (Wierman and Oliver 1979; Figures 2 and 3). In healthy stands with a foliage retention of 3.5, the relative basal area growth of western hemlock with the same size initial DBH ($i = 0$) declines as tree diameter increases from 2 to 12 in., due to natural differentiation patterns of the species mix rather than to relative species performance in absence of overtopping. Not surprisingly, as foliage retention declines with increasing SNC severity, combined Douglas-fir growth decline and increasing canopy light transmittance improve the relative performance of hemlock.

At foliage retention of 1.5 years, the most severe SNC depicted in this analysis, western hemlock outproduces individual Douglas-fir trees that are 1–2 in. larger in diameter depending in part on the initial diameter of the western hemlock (Figure 3). This difference would almost certainly be larger at lower foliage retention, although where foliage retention has remained at such a low level, optimal selection of residual trees in a thinning operation becomes considerably more obvious. To illustrate general application of the graphs, assume that a 6-in. western hemlock tree was growing next to a Douglas-fir tree in a stand with foliage retention of 2.0 years. In this case, the Douglas-fir tree would have to be 7.7 in. in diameter to produce the same basal area increment as the western hemlock. This conclusion, of course, is a consequence of the assumptions made to generate the field guides and represents the average growth pattern observed in plots from set of Swiss Needle Cast Corporative (SNCC) studies, including the GIS, PCT, CT, and RCT. Other factors that would enter into the decision include the relative stand-level productivity of the two species (partly reflected in diameter growth differences at a given stand density but also in maximum potential stand density, e.g., McArdle et al. (1961) versus Barnes (1962)), the relative value of the two species, and other stand management objectives besides timber production or maximization of economic return. Note also that under moderate to severe SNC the act of removing the adjacent Douglas-fir will produce a proportionately greater release effect on the growth of the residual western hemlock than removal of the western hemlock would have on the Douglas-fir. In other words, the charts developed from the growth equations (Figure 3) depict the current relative growth rates under current stand conditions, but differences ingrowth potential between the two trees are dynamic and will be even greater after thinning.

Under a stand management objective of maximizing economic return, conclusions from the analysis and graphs developed in this study would have to be further modified to the degree that market values of Douglas-fir and western hemlock diverge. In the third quarter of 2011, the delivered price for Number 2 Douglas-fir and western hemlock sawlogs in northwest Oregon was $530/mbf and $455/mbf, respectively, or a difference of $75/mbf. These prices during the same quarter 5 and 10 years earlier were approximately $580/mbf and $385/mbf, or a difference of $195.[1] During precommercial thinning operations, current log prices are not as important as long-term projections, so continued market fluctuations underscore the appeal of also considering relative growth potential of individual trees and corresponding stand-level differences in potential productivity.

Finally, the growth equations developed for this specific set of SNC-impacted stands provide insights into the altered stand dynamics of the specific subject population. They were developed to yield precommercial thinning guidelines for a relatively narrow geographic range, over a relatively short portion of a Douglas-fir rotation, and for a relatively narrow range in stand conditions. Long-term stand dynamics under SNC intensities that vary spatially and fluctuate temporally are largely unknown. Analyses using these equations can be complemented with predictions from more comprehensive regional growth models and other sources of information to confirm or modify developed guidelines and to compare the possible long-term consequences of alternative decisions about precommercial thinning in these stands. Although such projections must be recognized as gross extrapolations and interpreted with the same level of caution as the short-term implications of the equations developed here, the more information that can be brought to bear on decisions about managing these mixed-species, SNC-impacted stands, the more likely it is that stand management objectives will be met. We, therefore, strongly advocate that: (1) foresters apply the diameter growth equations in creative ways to develop guidelines for meeting their own stand management objectives for their own current stand conditions (i.e., Figure 3 is intended as only one very specific and simplified application); and (2) foresters combine the information from these equations with other lines of evidence to design strategies for stand management that will have the highest probability of achieving their objectives under uncertain future conditions.

Conclusion

The foliar losses of Douglas-fir imposed by SNC reduce Douglas-fir crown density and diameter increment, thereby enhancing diameter increment of western hemlock, the most common associate of Douglas-fir in coastal forests of Oregon. Application of Douglas-fir and western hemlock diameter increment models indicates that the relative basal area growth of the two species in young, mixed stands varies directly with foliage retention. When thinning in mixed stands where foliage retention is as low as 1.5 years, western hemlock trees will grow more in basal area than Douglas-fir tree that are 1–2 in. larger in diameter. These results can be useful for forest managers who can prescribe "$D + x$" thinning where x represents the diameter advantage that Douglas-fir must have over an adjacent western hemlock to be selected as the leave tree under the objective of providing comparable basal area growth over the short-term. In this approach, "x" would be selected as a function of SNC intensity as measured by foliage retention.

Endnote

1. Data obtained from www.oregon.gov/ODF/STATE_FORESTS/TIMBER_SALES/logpage.shtml.

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