Taper and Volume Responses of Douglas-Fir to Sulfur Treatments for Control of Swiss Needle Cast in the Coast Range of Oregon

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ABSTRACT

For nearly 20 years, foresters in the Oregon Coast Range have been witnessing a substantial decease in Douglas-fir (*Pseudotsuga menziesii* var. menziesii [Mirb.] Franco.) vigor and volume, caused by Swiss needle cast (SNC) disease. Currently, there are no solutions and disease severity is expected to worsen in coming years, but there is hope that aerially applied treatments of sulfur may be able to alleviate the effects of SNC. In this trial, volume, taper, and other attributes were examined on 120 Douglas-fir trees heavily infected with SNC for response to treatments of (1) sulfur, (2) sulfur + nutrients, and (3) control, which received no treatment. Tree attributes such as crown ratio, crown width, and sapwood area at crown base showed no statistically significant differences between treatments. Means of both foliage mass and years of needle retention also were not different between sulfur and control treatments. However, both of these attributes were different between the sulfur + nutrient and control treatments ($P = 0.0599, 0.0205$). Using a modified Kozak's (1988) variable exponent model form, taper analysis indicated that the taper of trees within the sulfur treatment was not significantly different from the taper of the control, while the sulfur + nutrient treatment showed decreased taper compared with the control ($P = <0.0246$). This improvement of taper in the sulfur + nutrient stand, however, has not translated into a statistically significant increase in cubic foot volume removed in the first thinning after adjusting for tree size differences between treatments. Comparing treatments by monetary value of removed trees in the first thinning also showed no significant differences, thereby implying that sulfur and sulfur + nutrient treatments are not able to increase volume enough in 4 years to produce additional profits in the first commercial thinning. It should be noted, however, that all conclusions drawn from this study are essentially from a single replication, and the scope of inference applies only to this particular type of stand in the Oregon Coast Range.

Keywords: tree form, forest nutrition, fertilization, mixed effects models, *Pseudotsuga menziesii*

The growth impact Swiss needle cast (SNC) has had on the Oregon Coast Range Douglas-fir *(Pseudotsuga menziesii* var. menziesii [Mirb.] Franco.) has been considerable. One of the earliest estimates of volume loss was approximated at 23% with a high of 50% in severely infected stands (Maguire et al. 1998). The SNC fungal pathogen, *Phaeocryptopus gauemannii*, clogs stomates of current-year needles and eventually leads to the premature loss of foliage, which affects both crown structure and dynamics (Weiskittel 2003). Weiskittel and Maguire (2004) also found that foliage retention (which is strongly negatively related to SNC severity) had a significant effect on stem taper. These authors reported that for a given tree dbh and relative height, a reduction in foliage retention significantly reduced diameter inside bark throughout the stem, except below breast height, thereby increasing the amount of taper in a tree with a higher level of SNC or poor needle retention.

In a direct attempt to lessen the impact of SNC, several recent studies have found that sulfur, which acts as not only a nutrient but also a fungicide, can decrease the incidence of the disease and improve foliage color and retention (Chastagner 2002, Stone et al. 2004). This parallels recent discoveries by Williams and Cooper (2003), which have revealed that many plants, including tomato, cotton, tobacco, and French bean, actually hold sulfur in their xylem for an induced defense response against certain types of fungi. The nutritional value of sulfur has been underestimated in the past as well. In the soil, sulfur (SO_4^{2-}) plays a pivotal role in the movement of acidic cations such as H^+ and Al^{3+}, as well as nutrient cations such as Ca^{2+} and Mg^{2+} (Johnson and Mitchell 1998). Furthermore, the increased use of fertilizers that contain little or no sulfur and the decrease in atmospheric sulfur deposition from reduced industrial emissions have resulted in an increasing soil sulfur deficiency worldwide (Jasinski et al. 1999). A constant ratio of 0.030 on a gram atom basis between organic S and total N has been found in the foliage of conifers (Kelly and Lambert 1972, Turner et al. 1979). The Oregon Coast Range is an area naturally rich in available nitrogen, which may have aggravated a sulfur deficiency in many areas in this region. It is common for Douglas-fir to exhibit a growth response to N + S treatment, but not to an N treatment alone (Garrison et al.

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2000). Analogous responses also have been observed in other conifers (Yang 1998, Brockley 2000).

In Oregon, Christmas tree growers effectively combat SNC by applying the fungicide Chlorothalonil, but this is not possible in forestry settings because of severely harmful effects on aquatic organisms. Alternatively, sulfur has been proven safe for aerial application in forests. The 2005 Material Safety Data Sheets reported sulfur to be "considered essentially nontoxic by ingestion," and "not expected to be toxic to aquatic life" (Baker 2004). Laboratory studies on the effectiveness of sulfur against SNC infection rates have been promising, and this guarantee of safety allows us to test sulfur's effectiveness in a large-scale industrial setting, as well as test taper and volume effects in these more mature stands.

The objective of this research project was to determine if tree crown and stem allometrics of Douglas-fir differ after 4 years of sulfur and sulfur + nutrient treatments. Specific objectives are to (1) test the influence of sulfur and sulfur + nutrient treatments on sapwood area, crown ratio, crown width, foliage biomass, and foliage retention; (2) test for stem taper differences among the treatments using a variable exponent taper model; and (3) compare cubic foot volume and log valuation removed in the first commercial thinning among treatments. It is hypothesized that aerial application of sulfur for consecutive years may be able to decrease the amount of taper, thereby increasing the diameter at the small end of logs taken out during the first thinning in the Oregon Coast Range.

Methods

Study Site

A Douglas-fir plantation located in the Nelsen Creek drainage of the Oregon Coast Range was selected by Starker Forests, Inc., in 2000 because of its fairly severe infection of SNC, its representation of typical Douglas-fir plantation management, and for being from a single source of Douglas-fir stock. This site is located at 44°43′N, 123°44′W in Lincoln County at approximately 530 ft in elevation with 5–10% slope. The soil is a gravelly loam to clay, with bedrock located 35–58 in. below the surface. Lincoln County's average annual rainfall is 75 in., the heaviest rains occurring in the Coast Range, where this site is located. The climate is influenced primarily by the Oregon Coast Range and prevailing westerly winds from the Pacific Ocean, which moderate temperatures. Minimal accumulations of snow occur, and only at higher altitudes, allowing for a growing season of approximately 200 days.

Experimental Design

Three units, approximately 2 square ac each, were delineated in the plantation. Each of these units was randomly assigned a treatment of (1) sulfur, (2) sulfur + nutrients, or (3) no treatment. The sulfur treatment consisted of 10 gal/ac of liquid sulfur, 20 gal/ac of water, and 8 oz of Tactic per 100 gal. This sulfur treatment was aerially applied twice in June 2002 and twice again in June 2003. The nutrient treatment was formulated specifically for this site and included calcium, dolomite, sulfur, potassium, boron, ferrous sulfate, copper sulfate, zinc sulfate, and urea and was applied annually from 2000 to 2004. Specific concentrations, spray rates, and spray years are shown in Table 1.

Table 1. Concentrations and rates of components in the nutrient treatment by year.

Amendment	Pounds/acre 2000	2001	2002	2004	Total
Calcium ($CaCO_3$)	540	540	540	1,000	2,620
Doloprill	1,440	1,440	1,440		4,320
Sulfur (90–92%)	25			35	60
Potassium (0–0-50)	250			300	550
Boron (14.3%)	15			15	30
Ferrous sulfate (26%)	270				270
Copper sulfate (23%)	10			15	25
Zinc sulfate (36%)	20			10	30
Urea (46–0-0)	440				440

Table 2. Min, mean, max, and standard deviation of selected tree attributes for the destructively sampled trees ($n = 120$ trees).

	Min	Max	Mean	Standard deviation
Total height (ft)	55.5	86.0	70.6	5.28
dbh (in.)	4.1	13.2	8.2	1.7
Crown ratio (%)	28.8	71.0	48.2	7.8
Crown width (ft)	2.1	14.5	8.8	1.9
Sapwood area (in.^{2})	1.5	58.4	18.5	9.5

Min, minimum; Max, maximum.

Table 3. Min, mean, max, and standard deviation of selected tree attributes of the subsampled trees and branches ($n = 30$).

	Min	Max	Mean	Standard deviation
Total height (ft)	64.7	80.1	73.4	3.9
dbh (in.)	7.5	14.0	10.0	1.3
Crown ratio (%)	41.5	69.5	52.0	6.9
Crown width (ft)	2.8	13.0	9.6	2.1
Sapwood area (in.^{2})	12.1	58.4	25.6	10.9
Needle biomass (oz)	2.5	28.4	12.0	5.8
Needle retention (yrs)	2.6	3.9	3.2	0.3

Min, minimum; Max, maximum.

The treatment sites were established in 2000 as part of a longer-term nondestructive study. Because the stand was due for the first commercial thinning, 40 trees per treatment, which showed no significant defect such as forks or conks, were selected at random and felled before the 2005 growth year began and used in the taper analysis (Table 2). The stand was 22 years old and had an average density of 407 trees/ac and an average basal area of 203 ft^2/ac at the time of felling. This completely randomized experimental design is flawed in that there is technically only one replication per treatment because the experimental unit is actually the 2-ac treatment block. To make the statistical analysis possible, each tree will be treated as if it is an experimental unit. It should be noted that all conclusions taken from this study are essentially from a single replication, and the scope of inference applies only to this particular type of stand in the Oregon Coast Range.

Fieldwork

Soon after felling, one south-facing sample branch was collected from the 5th whorl from the tree tip on a subsample of 10 trees per treatment (Table 3). The branches were returned to the laboratory and stored in a freezer until processing. The foliage was separated from the branch woody components, dried for 48 hours, and weighed to the nearest 0.01 g. To determine if the sulfur treatments improved needle retention (years of needles present), foliage age classes were recorded on the same 10 trees per treatment to the nearest 0.1 years.

Before removing any disks, branches (except the lowest live branch) were removed from the 120 felled trees and a cloth tape was laid on the length of the bole to measure tree height from the butt of the tree to the tip of the terminal bud. The height of each disk (h_i) was marked on the tree with an ax and measured with the cloth tape. Approximately nine disks were taken per tree: (1) stump height (approximately 6 in. to 1 ft from ground), (2) breast height, (3) crown base (lowest live branch), and (4) approximately six disks that fell between every third whorl above dbh. These last six disks were taken at interwhorls (halfway between every third whorl) to avoid complications with whorl swell. A chainsaw was used to remove disks and the top of the disk was labeled by plot number, tree number, and disk number and transported to the lab. In addition, diameters at 19, 38, and 57 ft above stump height were measured to the nearest tenth of an inch to determine the small end diameters of the 19-ft logs that would have been taken from the tree in a thinning. On each of the collected disks, two perpendicular measures of diameter inside and outside bark were taken to the nearest millimeter and then averaged. To obtain a sapwood area measurement, four radii measurements of heartwood were taken per crown base disk to the nearest millimeter. Sapwood area was indirectly obtained by subtracting heartwood surface area from total diameter inside bark surface area, assuming that the heartwood is circular in shape.

Crown ratio was defined as the measured distance between crown base to top of terminal leader divided by total tree height, where crown base is defined as the point on the bole where the lowest living branch exists. Two perpendicular branches from the whorl containing the lowest live branch were measured for crown width to the nearest tenth of an inch and then averaged to obtain crown width per tree.

Data Analysis

A one-way analysis of covariance (ANCOVA) was used to test for differences in sapwood area, crown ratio, crown width, branch diameter, foliage biomass, and foliage retention among the treatments at $\alpha = 0.05$. Because sapwood area often is considered to be directly proportional to tree leaf area (e.g., Waring et al. 1982), it was used as a proxy in determining if sulfur treatments could improve the leaf area of these infected crowns. When necessary, the response variable was transformed with a natural logarithm to stabilize the variance. For each attribute a selection of covariates were tested for additional explanation of variance; the one or two that explained the most variation were used in the final analysis. The generalized linear model procedure in SAS version 9.1 was used to conduct the one-way analysis of covariance (SAS Institute, Inc., Cary, North Carolina).

Kozak's (1988) variable exponent taper equation was used to explore the effect of treatment on stem taper. The original model can be written as

$$d_i = a_0 \mathrm{dbh}^{a_1} a_2^{\mathrm{dbh}} X^{b_1 Z^2 + b_2 \ln(Z+0.001) + b_3\sqrt{Z} + b_4 e^Z + b_5(\mathrm{dbh}/H)},$$

where d_i, the dependent variable, is diameter inside bark at a particular height (h_i) on the tree bole; dbh is diameter outside bark at breast height; Z is relative height (h_i/H), where H is total height; and X is $(1 - \sqrt{h_i/H})/(1 - \sqrt{p})$. The inflection point p is the relative height at which the tree shape changes from a neiloid to a paraboloid, for this data the inflection point was fixed at 25% of total height. Demaerschalk and Kozak (1977) found that in all commercial species of British Columbia this value only ranged between 20 and 25%; so estimating p with the data is not necessary. Last., $a_0 - a_2$ and $b_1 - b_5$ are parameters to be estimated. To test for treatment effects, two treatment indicators were added to the variable exponent portion of the model, these being I_S (one if trees are sulfur treated and zero otherwise) and I_{SN} (one if trees are sulfur + nutrient treated and zero otherwise).

Data sets used to develop taper equations inherently contain autocorrelation. Ignoring correlated errors is a valid option; however, this option results in (1) estimators that no longer have a minimum variance property, (2) underestimation of the mean square error and standard errors of parameter estimates, and (3) unreliable statistical tests using t or F-distributions, as well as unreliable confidence intervals (CI; Kozak 1997). Because an accurate estimation of standard error for the treatment coefficient was essential to this analysis, the autocorrelation was accounted for with a combination of a continuous autoregressive error structure (CAR(1)) and a random tree effect (a nonlinear mixed effects technique). These techniques have repeatedly been proven effective for providing meaningful tests of significance in modern taper analyses (Tasissa and Burkhart 1998, Garber and Maguire 2003). Error increased with diameter of tree disks violating the assumption of constant variance. Therefore, a power variance function was incorporated into the fitting procedure. After examining a number of weighting functions, it was determined that 0.3 significantly improved the fit of the data ($P = <0.0001$). Evaluation of assumptions for testing parameters were assessed with residual and empirical autocorrelation plots at $\alpha = 0.05$ (Pinheiro and Bates 2000). Nested models were compared using likelihood ratio tests and included tests on random effects, variance functions, and correlations structures (Pinheiro and Bates 2000, Garber and Maguire 2003). Models were fitted with S-PLUS 7.0 (Insightful Corp., Seattle, WA).

The Smalian's formula was used to estimate the cubic foot volume of the 19-ft logs that would have been taken in a thinning had these trees not been used for taper analysis. Cubic foot volume was calculated by log in each treatment up to a diameter of 4 in. inside bark. All trees produced two logs above stump height, while a few produced three. An ANCOVA was performed after a log transformation of the cubic foot volume to correct a strong nonconstant variance. A dbh covariate was incorporated to adjust for tree size; this was necessary because the subject trees were randomly selected at each plot, and average tree size was slightly different, but not statistically so, between treatments (control-sulfur P-value = 0.6556, control-sulfur + nutrient P-value = 0.6648, and sulfur-sulfur + nutrient P-value = 0.9898).

To quantify volume differences between treatments monetarily, Scribner board foot volume was determined for each tree. Board foot volumes were calculated based on a 1972 Scribner factor table to the nearest inch diameter (Bell and Dilworth 2002). Nineteen-foot saw logs were taken to a 5-in. small end diameter inside bark (DIBSE), and 19-ft pulp logs to a 2-in. DIBSE were taken from the remainder. Values (in dollars) per tree were obtained through the use of the Oregon Department of Forestry Region 1, 2006, 2nd quarter log price report. Saw logs, all assumed to be 3-saw quality, have a value of \$595/thousand board feet (mbf) and the value of pulp logs (utility) is \$55/mbf.

Results

Crown Allometrics

ANCOVA on sapwood area at crown base with diameter inside bark at brown base as the covariate revealed that the sulfur treatment has 1.05 times more sapwood than the control (95% CI, 0.95–1.16) and the sulfur + nutrient treatment has about the same sapwood area as the control (0.99 times more than control; 95% CI, 0.90–1.10). Statistically, neither of these were significantly different from the control ($P = 0.9363$ and 0.6653, respectively) and the sulfur treatment was not significantly different from the sulfur + nutrient treatment ($P = 0.7240$).

Using total height as a covariate (which accounted for 21% of variation) in the crown ratio model, mean crown ratios were 50, 47, and 48% for the control, sulfur, and sulfur + nutrient treatments, respectively. Neither of the treatments are significantly different from the control (control-sulfur comparison, $P = 0.1353$; control-sulfur + nutrient comparison, $P = 0.1648$).

Of all possible covariates, sapwood area accounted for the most variation in crown width (29%). With this covariate it was determined that the sulfur and control treatments had a mean crown width of 8.9 ft, and the sulfur + nutrients treatment had a width of 8.5 ft. Similar to sapwood area and crown ratio, the treatment comparisons indicate no statistical significance (control-sulfur comparison, $P = 0.5073$; control-sulfur + nutrient comparison, $P = 0.8517$).

Branch Size, Biomass, and Foliage Retention

The treatments showed a significant relationship with branch diameter after accounting for branch height. For a given branch location (feet aboveground) and tree size (dbh), branch diameter was 11.9% larger for the sulfur + nutrient treatment when compared with the control ($P = 0.0361$). There was no significant difference in branch diameter between the sulfur-only treatment and the control.

After accounting for branch location (feet from the ground) and tree size (dbh), foliage biomass was not significantly different between the sulfur treatment and the control ($P = 0.9094$), but there was moderate evidence that the sulfur + nutrient treatment was significantly different from the control ($P = 0.0599$).

Again accounting for branch location and tree size, the mean years of needles retained in the sulfur + nutrient treatment, 3.4, was significantly greater than the mean years of needles retained in the control treatment, 3.0 ($P = 0.0205$). This same statistical significance, however, is not seen between the sulfur and control treatments ($P = 0.2496$) where the sulfur treatment's mean retention was only 3.2 years.

Stem Taper

To draw proper conclusions about the effect of sulfur and sulfur + nutrients on taper, Kozak's (1988) taper model was refined. The α_2-parameter, which helps to describe inside bark diameter from dbh, was eliminated because of very high parameter correlations and an insignificant P-value. The redundancy of the Z variable in the exponent parameters b_2, b_3, and b_4 led to an examination of the necessity of all three of these parameters. It was determined that eliminating the b_2 parameter improved Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) as well as the log likelihood ratio. Thus, further analysis was conducted without the b_2 parameter. The final model form can be written as

$$d_i = a_0 \mathrm{dbh}^{a_1} X^{b_1 Z^2 + b_3 \sqrt{Z} + b_4 e^z + b_5(\mathrm{dbh}/H) + b_6 I_S + b_7 I_{\mathrm{SN}}}.$$

Table 4. AIC, BIC, and log-likelihoods are presented between taper models with and without a random effect and a CAR(1).

Error structure	Estimated parameters	AIC	BIC	Log likelihood
GNLS	10	8,428	8,478	−4,204
GNLS with CAR(1)	11	7,955	8,009	−3,966
NLME	11	8,342	8,397	−4,160
NLME with CAR(1)	12	7,958	8,018	−3,967

GNLS, generalized nonlinear least squares model without a correlation structure or random tree effect; NLME, nonlinear mixed effects model fit by maximum likelihood with a single random tree effect; CAR(1), continuous autoregressive error structure with a log of one.

In determining the best taper modeling technique, AIC, BIC, and the log likelihood ratio are presented between models with and without a random effect and a CAR(1) (Table 4). A first-order autoregressive process was found adequate in accounting for the significant autocorrelation and was superior to the random tree effect model (Figure 1). The addition of a random tree effect to the CAR(1) model did not significantly improve the fit (Table 5).

Tests on the two indicator variables suggested that taper in the sulfur treatment was not statistically different from the reference treatment, the control (e.g., b_6 was not significantly different from zero, $P = 0.7160$). However, the sulfur + nutrient treatment did have significantly less taper than the control treatment indicated by b_7 being significantly less than zero ($P = 0.0246$). Because the sulfur + nutrient treatment shows a significantly improved taper, using a different set of taper coefficients is suggested (Table 6; Figure 2).

Stem Volume

Cubic foot volume to a 4-in. inside bark diameter showed no significant differences among the treatments. After correcting for tree size with dbh, the control treatment had a mean tree volume of 12.08 ft^3, the sulfur treatment had a mean of 11.19 ft^3, and the sulfur + nutrient treatment had a mean of 11.59 ft^3 (control-sulfur comparison, $P = 0.0957$; control-sulfur + nutrient comparison, $P = 0.3441$).

Because smaller-diameter logs are worth considerably less than saw logs, dollar values were calculated per tree using the aforementioned mbf prices. Much like the results in the examination of cubic feet between treatments, this mbf log valuation implies that there are no treatment differences in the value of thinned trees after accounting for tree size with a dbh covariate (control-sulfur comparison, $P = 0.6850$; control-sulfur + nutrients comparison, $P = 0.6969$). Surprisingly, the control treatment actually has the greatest mean dollar value ($25.98), although this is not statistically significantly different from the other two treatments, where the average value of a sulfur-treated tree is $25.32 and a sulfur + nutrient–treated tree is $25.35.

Discussion

Originally, sapwood area at crown base was hypothesized to be greater in the sulfur-treated stands because of increase in foliage retention and a concurrent increase in leaf area; this, however, was not observed. Neither the sulfur nor the sulfur + nutrient treatment showed a statistically significant increase in sapwood area, despite an

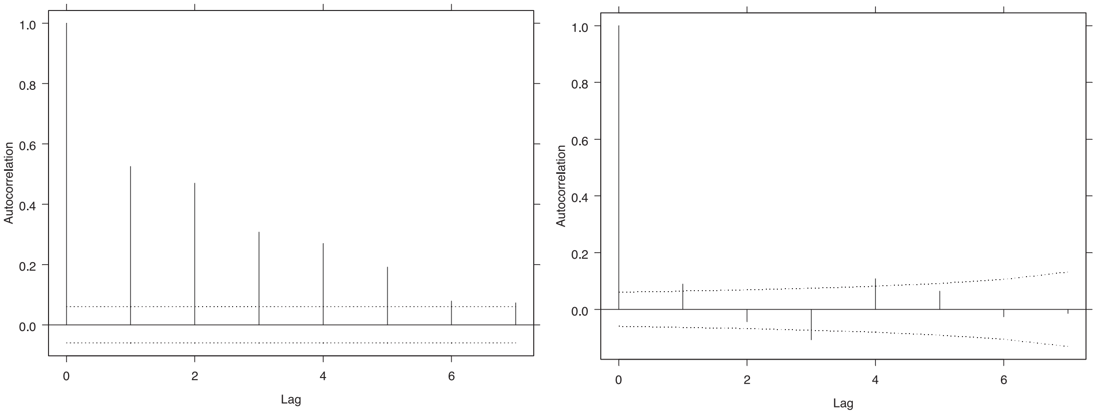

Figure 1. Autocorrelation plots for the original GNLS model form (left) and the final model form, GNLS with a CAR(1) (right).

Table 5. List of likelihood ratio tests and corresponding *P*-values for determining best taper model error structure, where GNLS with CAR(1) is determined to be the best, followed closely by NLME with CAR(1).

Test	Likelihood ratio	*P*-value	Conclusion
GNLS vs. GNLS with CAR(1)	475	<0.0001	Adding CAR(1) improved GNLS model
NLME vs. NLME with CAR(1)	386	<0.0001	Adding CAR(1) improved NLME model
GNLS vs. NLME	88	<0.0001	NLME alone is better than GNLS alone
GNLS with CAR(1) vs. NLME with CAR(1)	2	0.1688	Adding random effect was not statistically better

Table 6. Taper model coefficients with corresponding standard errors listed for the two significantly different treatments, control and sulfur + nutrients.

Control treatment			Sulfur + nutrient treatment		
Parameter	Estimate	Standard error	Parameter	Estimate	Standard error
a_0	1.0609	0.1177	a_0	1.8422	0.3506
a_1	0.9442	0.0203	a_1	0.8427	0.0354
b_1	0.1403	0.0834	b_1	0.3942	0.1293
b_3	−1.1015	0.1011	b_3	−1.1917	0.1306
b_4	0.6266	0.0565	b_4	0.5599	0.0881
b_5	0.0132	0.0042	b_5	0.0180	0.0077

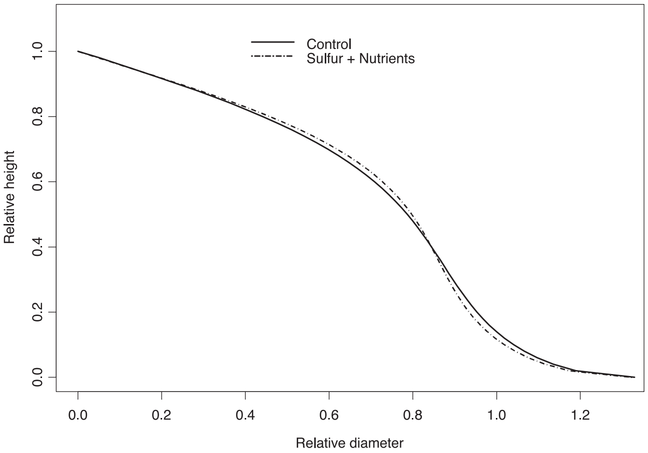

Figure 2. Graphical display of taper difference between the control and sulfur + nutrients treatments.

increase in foliage biomass and needle retention in the sulfur + nutrient treatment. This may be caused by a delay in the amount of time required for an increase in leaf area to show itself in sapwood area. This also may be related to changes in sapwood anatomy after fertilization improving conductivity, such as decreases in ring density, percent latewood, and increases in lumen diameter (Mäkinen et al. 2002).

There was a slight, albeit insignificant, decrease in crown ratio in the treated stands. There also was no apparent effect on crown width. These results were not unexpected as previous research has suggested that the impact of SNC on these gross measures of crown size has been shown to be very minimal—slightly increasing crown recession and crown profile in the lower crown third (Weiskittel 2003). The decrease in crown ratio may reflect a slight fertilization effect (e.g., Albaugh et al. 2006).

More interestingly, the sulfur + nutrient treatment did increase branch size, needle retention, and foliage biomass measured on an upper crown branch. This result suggests that the sulfur + nutrient treatment may increase foliage biomass at the whole tree level. The increase in foliage biomass was likely a result of this greater needle retention (sulfur effect) and an increase in younger foliage development (nutrient effect). An increase in leaf area after fertilization has been reported in forestry literature (e.g., Brix 1981). Although not significant, there was a slight increase in needle retention in the sulfur treatment, suggesting a slight effect of sulfur on the pathogen. Needle retention has been shown to decrease with greater site fertility (e.g., Xiao 2003 and Amponsah et al. 2005). Along these lines, fertilization also has been shown to cause a decrease in needle retention (e.g., Balster and Marshall 2000); our contradictory results of an increase in needle retention in the sulfur + nutrient treatment may be caused by a stronger fungicidal effect than nutrient effect.

After finding an improvement of foliage biomass and retention in the sulfur + nutrient treatment, it was not surprising to find that this treatment also slightly decreased taper. Stem cross-sectional area increment generally increases with greater foliage, but the increase is not proportional (Kershaw and Maguire 2000). Because the pathogen infects the most productive current-year needles, which are skewed to the top of the tree, area increment reduction is greatest at upper stem portions relative to healthy trees (Weiskittel and Maguire 2004). The effect of the sulfur + nutrients to improve foliage retention and biomass ameliorates this growth impact, resulting in vertical stem increments similar to healthier trees, resulting in less taper.

The addition of the random tree effect in the taper model was not necessary. Adding the random effect to the generalized nonlinear least squares (GNLS) with CAR(1) model resulted in slightly larger AIC and BIC values and a statistically insignificant log-likelihood ratio ($P = 0.1688$). Because this difference was insignificant, the simpler model, GNLS with CAR(1), was chosen. This result, however, was contradictory to more recent studies in which mixed modeling significantly improved the model fit. Garber and Maguire (2003) found that when modeling stem taper in differing tree spacings, the combination of random effects and a first-order autoregressive process was necessary to reduce the effect of autocorrelation. Tasissa and Burkhart (1998) also recognized and accounted for correlation among within-tree observations with mixed modeling techniques but noted that some of the variables that were significant when correlation was ignored turned insignificant after correlation was accounted for and visa versa. It is important to note that in this analysis a change in significance was noticed also. The sulfur + nutrient treatment remained significant after accounting for the variance with a power function ($P = 0.0016$) and adding a CAR(1) to account for autocorrelation ($P = 0.0246$). However, this treatment became insignificant once a random tree effect was added ($P = 0.1364$). Because the random effect was determined to be unnecessary, however, it was not used, leaving the sulfur + nutrient treatment to remain significant. Huang et al. (2000) knowingly chose not to use mixed modeling techniques when modeling taper with a variable-exponent model form, stating that whether the correlations are accounted for has little practical significance for prediction purposes. Gregoire et al. (1995) argued that model misspecification caused by erroneously including or excluding covariates because of their inaccurate error estimates can bias the model fitting process, therefore possibly damaging predictions. Despite these views of mixed modeling of taper models, the random effect was left out of this analysis because of the increase in AIC and BIC.

The financial justification for sulfur treatments in SNC-infected stands was expected to partially come from an increase in volume produced in the first commercial thinning. The improvement in taper in the sulfur + nutrient treatment was hypothesized to result in more 19-ft logs to move into the sawlog category, which brings approximately 10 times the dollar value than the pulp logs. However, both the cubic foot volume results as well as the log valuation revealed no significant differences between treatments in this stand. This implies that there may be no volume benefit to the sulfur or the sulfur + nutrient treatments. This insignificance could be caused by a lack of a sufficient time period for the increased growth rate to reveal itself in total volume, but whether the DIBSE will improve enough in the next couple of years to receive a total volume benefit remains to be seen. As interesting as these results may be, it should be kept in mind that all conclusions drawn from this experiment were from a single replication. The same study done elsewhere may produce contradicting results. Replication also might reveal whether sulfur treatments on stands with different degrees of SNC severity or different site classes might show a greater response.

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