INTENSIVE MANAGEMENT INFLUENCE ON DOUGLAS FIR STEM FORM, BRANCH CHARACTERISTICS, AND SIMULATED PRODUCT RECOVERY*

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ABSTRACT

Intensive management may adversely affect lumber yield and quality by increasing knot size and creating a more conical stem form with a greater average rate of taper. This study was initiated to examine the impact of management on simulated lumber yield and quality. Stem diameter and branch size and location of 223 *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir) stems ranging in age from 5 to 65 years and from a wide variety of stand conditions were intensively measured. Stand conditions included varying levels of vegetation management, precommercial thinning, commercial thinning, fertiliser application, and severity of infection by *Phaeocryptopus gaeumannii* (Rohde) Petrak (Swiss needle cast). In addition, 86 virtual logs were created and processed by AUTOSAW. Significant changes in both stem form and branch characteristics were observed among the stand conditions examined, with maximum branch size being the most

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responsive to silvicultural regime and disease severity. Changes related to fertiliser and thinning were not significant enough to adversely affect simulated lumber quality and yield. Indices of branch size were poor predictors of simulated log grade yield. Although quantification of branch size and location is important for understanding crown structure, growth potential, and the vertical distribution of biomass, factors such as juvenile wood percentage and wood density may exert more control over simulated product quality in the young Douglas fir analysed in this study.

Keywords: plantation management; AUTOSAW; stem taper; crown structure; *Pseudotsuga menziesii*.

INTRODUCTION

As log sizes continue to decline and large timber purchasers specify requirements beyond normal visual grading rules, silvicultural control of wood quality assumes increasing importance in the North American Pacific Northwest. Research has previously shown that trees harvested at age 40–60 years do not produce the same log and lumber grade yields as those harvested at age 70–100 years, because they have larger branches and more juvenile wood (Barbour & Parry 2001). Only a limited amount of research, however, has been done on the influence of intensive management activities such as vegetation control, precommercial thinning, and fertiliser application on wood quality characteristics (Sonne *et al*. 2004; Gartner 2005). Qualitatively, it has been suggested that these activities will increase juvenile wood content and knot size (Fahey *et al*. 1991; Gartner 2005). However, gains in lumber yield may significantly outweigh any negative consequences for log or product quality (Sonne *et al*. 2004).

Two of the most important individual tree attributes that are highly sensitive to stand condition and influence lumber quality are stem form and branching characteristics. Research on the response of these attributes to intensive management has been limited and not highly conclusive, particularly for branch responses. For example in *Picea abies* (L.) Karst (Norway spruce), Mäkinen *et al*. (2001) found that branch diameter growth of both newly initiated and older branches was significantly enhanced with fertiliser, but Mäkinen *et al*. (2004) indicated that variables describing site fertility and fertiliser regime were not significantly related to branch radial growth. Similar discrepancies can be found for the effects of site or disease condition on stem form.

This study was initiated to test the influence of intensive management on Douglas fir log quality, in light of limited and conflicting published results. Specific objectives of the work were to: (1) test the effects of silvicultural treatments and stand conditions on the two primary tree and log attributes that influence lumber recovery and quality (stem form and branch characteristics); (2) test for change in simulated lumber yield and quality implied by any changes in stem form and branch characteristics; (3) compare results with the quantitative models proposed by Fahey *et al.* (1991) and update models if necessary.

METHODS

Study Sites

The majority of the sites utilised in this study were located in the northern Oregon Coast Range (lat. 45º to 46ºN, long. 123º10' to 124ºW). Other study site locations included two installations in the Oregon Cascade foothills (lat. 45ºN, long. 122º30'W), one installation in the southern Washington Cascade foothills (lat. 46º50'N, long. 122º00'W), and an installation in the Willamette Valley (lat. 44º5'N, long. 123º20'W), situated between the Oregon Coast Range and Cascades. The climate in this study area is humid oceanic, with a distinct dry summer and a cool, wet winter. Rainfall varies from approximately 100 to 300 cm/year and January mean minimum and July mean maximum temperatures range from –2° to 2°C and from 20° to 28°C, respectively. Variation in precipitation and temperature for this area is strongly correlated with elevation and proximity to the coast. Elevation ranged from sea level to 825 m, and all topographical aspects were represented in the data.

The plantations in which plots were established were 5 to 65 years old at breast height and contained ≥75% Douglas fir by basal area, with varying amounts of naturally regenerated *Tsuga heterophylla* (Raf.) Sarg. (western hemlock) and other conifer and hardwood species.

Data Collection

Several datasets were combined to test the effects of a variety of silvicultural treatments and stand conditions (Table 1). In 2002 and 2003, 122 Douglas fir trees were sampled from 33 plantations with varying levels of Swiss needle cast (Weiskittel *et al.* 2006). In 2004, three additional datasets were constructed from: 19 sample trees on three pre-commercial thinning installations (Swiss Needle Cast Cooperative, Oregon State University; Maguire *et al.* 2004), 52 trees from four Stand Management Cooperative installations (University of Washington; Maguire *et al.* 1991), and 30 trees from two Vegetation Management Research Cooperative installations (Oregon State University; Rose & Rosner 2005). All sample trees were measured for diameter at breast height (dbh), total height (HT), height to crown base (HCB; lowest live branch), and specific attributes described below. Finally, extensive data sets on stem form maintained by both the Stand Management Cooperative and Vegetation Management Research Cooperative were used to supplement the dataset constructed in this study to ensure correct model behaviour and examine a wider array of treatments (e.g., pruning, heavy thinning).

TABLE 1–Description of plots sampled for stem form and branch attributes. The Stand Management Cooperative Type 1 plots were used in the AUTOSAW simulations.

Study	Location	Plot	Treatment
SMC Type 1	Coast Range, OR	1	Planted 905 trees/ha in 1984; Heavy thinning; RD45—>RD25, RD50—>RD35, subsequent RD55—>RD40
		2	Planted 905 trees/ha in 1984
		3	Planted 905 trees/ha in 1984; ISPA/4
		4	Planted 905 trees/ha in 1984; ISPA/2, minimal thinning; RD55—>RD35, no further thinning, apply 224 kg N/ha as urea every 4 years
		5	Planted 905 trees/ha in 1984; Repeated thinning: RD55—>RD35, RD55—>RD40, subsequent RD60—>RD40, apply 224 kg N/ha as urea every 4 years
		6	Planted 905 trees/ha in 1984; ISPA/4, no further thinning, apply 224 kg N/ha as urea every 4 years
SMC Type 1	Cascade foothills, OR	1	Planted 1000 trees/ha in 1982; Repeated thinning: RD55—>RD35, RD55—>RD40, subsequent RD60—>RD40, apply 224 kg N/ha as urea every 4 years
		2	Planted 1000 trees/ha in 1982; ISPA/2, minimal thinning: RD55—>RD35, no further thinning, apply 224 kg N/ha as urea every 4 years
		3	Planted 1000 trees/ha in 1982; Heavy thinning: RD45—>RD25, RD50—>RD35, subsequent RD55—>RD40
		4	Planted 1000 trees/ha in 1982
SMC Type 1	Cascade foothills, WA	1	Planted 1075 trees/ha in 1981; Repeated thinning; RD55—>RD35, RD55—>RD40, subsequent RD60—>RD40, apply 224 kg N/ha as urea every 4 years
		2	Planted 1075 trees/ha in 1981; Repeated thinning; RD55—>RD35, RD55—>RD40, subsequent RD60—>RD40
		3	Planted 1075 trees/ha in 1981
		4	Planted 1075 trees/ha in 1981; ISPA/2, minimal thinning: RD55—>RD35, no further thinning, apply 224 kg N/ha as urea every 4 years
SMC Type 3	Willamette Valley, OR	1	Planted at 247 trees/ha in 1988
		3	Planted at 762 trees/ha in 1988
		6	Planted at 3048 trees/ha in 1988

TABLE 1–cont.

Study	Location	Plot	Treatment
VMRC	Coast Range, OR	1	Planted in 1993
		2	Planted in 1993; only woody vegetation controlled on 0.04-ha plot for 3 years
		3	Planted in 1993; only herbaceous vegetation controlled on 0.04-ha plot for 3 years
		4	Planted in 1993; competing vegetation controlled on 3.34 m^2 around planted trees for 3 years
		5	Planted in 1993; competing vegetation controlled on 9.29 m^2 around planted trees for 3 years
VMRC	Cascade foothills, OR	1	Planted in 1993
		2	Planted in 1993; only woody vegetation controlled on 0.04-ha plot for 3 years
		3	Planted in 1993; only herbaceous vegetation controlled on 0.04-ha plot for 3 years
		4	Planted in 1993; competing vegetation controlled on 3.34 m^2 around planted trees for 3 years
		5	Planted in 1993; competing vegetation controlled on 9.29 m^2 around planted trees for 3 years
SNC GIS	Coast Range, OR	-	24 stands planted from 1970 through 1986; some plots precommercially thinned prior to 1996
SNC CT	Coast Range, OR	-	9 stands planted from 1942 through 1972; no thinning since 1994
PCT	Coast Range, OR	1	Planted in 1990
		2	Planted in 1990; thinned to 500 trees/ha in 1998
		1	Planted in 1988
		2	Planted in 1988; thinned to 250 trees/ha in 1998
		1	Planted in 1986
		2	Planted in 1986; thinned to 500 trees/ha in 1998

SMC	Stand Management Cooperative	PCT	Precommercial thinning
VMRC	Vegetation Management Research Cooperative	RD	Relative density
SNC GIS	Swiss needle cast growth impact study	ISPA	Initial spacing
SNC CT	Swiss needle cast commercial thinning study		

Swiss needle cast

A growth impact study was initiated by the Swiss Needle Cast Cooperative in 1998, encompassing 76 permanent plots (0.08-ha) established in relatively young (10- to 30-year-old) Douglas fir plantations with varying levels of Swiss needle cast (Maguire *et al.* 2002). A commercial thinning study was also established in 30 older (30- to 60-year-old) plantations in the same year (Mainwaring *et al.* 2005). Each plot has been assessed annually for Swiss needle cast severity and measured for growth every 2 years. Data were collected from 86 sample trees adjacent to the growth impact plot in 24 young plantations and 36 sample trees in nine older plantations. Plots sampled in the older plantations included the unthinned control plots in a paired-plot study as well as thinned plots in a retrospective study that had accrued 3–5 years of growth since thinning. Three to four trees per installation were felled, and location and diameter of every living primary branch (≥1 mm diameter) were measured to determine total foliage mass (Weiskittel *et al.* in press).

Pre-commercial thinning

Pre-commercial thinning installations were established across a range of Swiss needle cast severity in 1998 and thinned in the same year. Most of these installations contained a pair of square 0.08-ha plots, one thinned to 494 trees/ha and the other an unthinned control. Five installations contained an additional plot that was thinned to 247 trees/ha. In this study, three relatively healthy installations containing all three plots were selected. At each installation, the control plot and one randomly chosen thinning level were measured, resulting in one heavy thinning treatment and two light thinning treatments. Within each plot, three trees were randomly selected at the 25th, 63rd, and 93rd diameter percentile. Each tree was then climbed and every branch (living + dead) from ground line to the third whorl from the tree tip was measured for height of insertion and diameter. All measured branches were also coded as either north or south. A subsample of branches was measured for aspect (azimuth to nearest degree), angle of insertion, total length, and non-foliated length, then tagged for future reference.

Stand Management Cooperative

Since its inception in the mid-1980s, the Stand Management Cooperative has maintained a database covering 400 installations in British Columbia, Washington, and Oregon. Each installation has numerous square 0.2-ha plots that are scheduled for a variety of silvicultural treatments including density control, pruning, and fertiliser application. The Stand Management Cooperative has established 30 initial spacing trials (Type 3) that have at least five square 0.2-ha plots with planting densities ranging from 247 to 3048 trees/ha. Type 1 installations were established in young plantations and have received differing silvicultural regimes since plot establishment. Three respacing trials (Type 1 installations) that included fertiliser treatments were selected, one each in the Oregon Coast Range, south-western Washington Cascades, and western Oregon Cascades. One initial spacing trial (Type 3 installation) was also selected in the Willamette Valley.

At each installation, four plots were chosen and three trees were randomly selected at the 25th, 63rd, and 93rd diameter percentile within each plot. In the respacing trials (Type I) the four selected plots included the untreated control, a plot respaced to leave 50% of the initial number of trees (THIN), a plot treated with 448 kg N/ha as urea nitrate (FERT), and a plot receiving both the fertiliser and thinning treatments (THIN+FERT). Fertiliser treatments were implemented 1 to 4 years prior to tree sampling and measurement. In the Type 3 installation, the three selected plots were planted at densities of 247, 762, and 3048 trees/ha. Similarly to the precommercial thinning dataset, each tree was climbed and every branch (living + dead) from ground level to the third whorl from tree tip was measured for height of insertion and diameter. All measured branches were also coded as either north or south. A subsample of branches was measured for aspect, angle of insertion, total length, and non-foliated length.

Vegetation Management Research Cooperative

Two Vegetation Management Research Cooperative installations, one in the central Oregon Coast Range and the other in the lower Cascade foothills, were established in 1993 and have received varying levels of vegetation control (Rose & Rosner 2005). Eight treatments at each installation were randomly assigned to three plots each. The plots covered 0.04 ha and had a 6-m buffer on each side. In this study, the following five treatments were selected: the untreated control, 3.34 m^2 of total vegetation control (TVC) around each tree, 9.29 m^2 of total vegetation control around each tree, complete removal of only woody vegetation from the entire plot (WDY), and complete removal of only herbaceous vegetation from the entire plot (HRB). Plots at each installation were randomly selected from the three available for each treatment, and three trees were randomly selected near the 25th, 63rd, and 93rd diameter percentiles within each plot. Each tree was then climbed and every branch (living + dead) from ground level to the third whorl from tree tip was measured for height of insertion and diameter. All measured branches were also coded as either north or south. A subsample of branches was measured for aspect, angle of insertion, total length, and non-foliated length.

AUTOSAW simulations

Lumber quantity and quality produced to date by the various Stand Management Cooperative silvicultural regimes was assessed by simulated sawing of sample tree logs using AUTOSAW (Todoroki 1990). Simulations were done on trees from

Stand Management Cooperative plots because the treatments were replicated in a controlled experiment, all branches were measured rather than just live ones, and the stands were closer to maturation (~25–30 years) than stands in the other datasets. Each stem (n=44) was divided into two 4.88-m logs, each log was characterised by location and size of whorls and branches, and lumber recovery was simulated by running these logs through AUTOSAW. A mill specification file similar to the one presented by Todoroki *et al*. (2005) was used for all simulations.

Data analysis

Treatment effects on diameter at breast height, total height, and height to crown base were tested by analysis of variance. Stem form, number of branches per whorl, branch angle of insertion, and branch diameter were modelled with various linear and nonlinear regression equations for each dataset. Treatment effects were then tested by addition of indicator variables. Initial model forms were selected from those presented by Kozak (2004) for taper, Maguire *et al*. (1994) for branch number and angle, and Maguire *et al.* (1999) for maximum branch diameter profile. Final models were chosen on the basis of residual analysis, Akaike's information criterion, and biological interpretability.

Multiple measurements within trees, within plots, and within installations imposed a hierarchical structure on the data. Error terms in the regression models were therefore not independent and uncorrelated, and so a multi-level, mixed-model analysis was performed. In this analysis, random effects of tree, plot, and installation were estimated. When heteroskedasticity was detected in the residual plots, the final equation was weighted by a power variance function of the primary independent variable. Where needed, a continuous first-order autoregressive term was introduced as a function of distance from the tree tip to reduce any remaining autocorrelation within trees. Likelihood ratio tests were used to compare nested model forms.

For each AUTOSAW log, lumber yield and quality were summarised and used to calculate total lumber volume, cubic lumber recovery (ratio of recovered lumber volume to actual log volume), a volume weighted grade average (Todoroki *et al.* 2005), and estimated value based on 2004 mean prices. The cubic lumber recovery is a measure of the actual cubic volume of lumber recovered from the original net cubic log scale volume and is influenced by log size and form. Cubic lumber recovery ranges from 0 to 1 and should not be confused with lumber recovery factor, which can be greater than 1. The weighted grade average is an indicator of the recovered products quality and is calculated by giving weights to each product class. In this study, a weight of 3 was assigned to grade No. 1 and better, a 2 to No. 2, and a 1 to No. 3 and Economy. These grades were based on United States Western Wood Products Association specifications (Table 2). Treatment effects were tested by analysis of covariance with installation, log location (lower *vs* mid), and log size

TABLE 2–Description of the grades used in this study, based on United States Western Wood Products Association specifications.

Grade	Description
No. 1 and better	Sound, firm, encased, and pith knots are limited up to no larger than 22 mm. They must be tight and well spaced. Unsound or loose knots or holes are limited to no larger than 19 mm, with one per 1.2 m allowed.
No. 2	Knots must be of the same type as in No. 1 and better grade, with size no greater than 38 mm. Unsound or loose knots or holes are limited to no larger than 25 mm, with one allowed per 91 cm. Wane is allowable, up to $^1/_4$ the thickness and $^1/_4$ the width full length, or equivalent on each face, provided that wane not exceed $^1/_2$ the thickness or $^1/_3$ the width for up to $^1/_4$ the length.
No. 3	Well-spaced knots of any quality are allowable in sizes up to 51 mm, with one hole up to 32 mm in diameter allowable per 61 cm. Wane is allowable, up to $^1/_3$ the thickness and $^1/_3$ the width full length, or equivalent on each face, provided that wane not exceed $^2/_3$ the thickness or $^1/_2$ the width for up to $^1/_4$ the length.
Economy	Knots must be of the same type as in No. 3 grade. Wane is allowable, up to $^1/_2$ the thickness and $^1/_2$ the width full length, or equivalent on each face, provided that wane not exceed $^2/_3$ the thickness or $^1/_2$ the width for up to $^1/_4$ the length.

as covariates. Treatment effects were also tested by modelling lumber recovery factor as a function of small- and large-end log diameter and testing the marginal effects of branch diameter and branch number. A system of equations to estimate percentage of lumber recovery in each of the grades was fitted with iterative seemingly unrelated regressions to account for cross-equation correlation and force additivity.

RESULTS

Across all studies, sample trees ranged from 5 to 67 cm dbh and 3 to 46 m total height (Table 3). The smallest trees were sampled on the Vegetation Management Research Cooperative plots, and the largest on the Swiss needle cast plots. The range in maximum whorl branch diameter paralleled that of tree size, ranging from 2.9 to 42.2 mm on Vegetation Management Research Cooperative trees and from 2.6 to 91.6 mm on Swiss needle cast trees (Table 4).

TABLE 3–Attributes of the sample trees used in the stem form and branch analysis.

Measure	Diameter at breast height (cm)	Total height (m)	Height to base of crown (m)
Stem form			
Stand Management Cooperative (n_{tree}=503; n_{disc}=7853)			
Mean	19.5	16.2	6.2
Std	7.3	4.9	3.6
Min	4.7	5.1	0.2
Max	43.8	27.4	17.5
Vegetation Management Research Cooperative (n_{tree}=233; n_{disc}=1643)			
Mean	10.7	7.8	0.7
Std	2.6	1.4	0.4
Min	2.3	2.7	0.1
Max	21.2	14.7	2.3
Swiss needle cast (n_{tree}=105, n_{disc}=1385)			
Mean	32.5	25.5	11.2
Std	11.1	8.4	3.84
Min	12.5	11.9	4.94
Max	66.6	45.8	28.3
Precommercial thinning (n_{tree}=19; n_{disc}=110)			
Mean	23.3	14.8	2.1
Std	6.3	3.2	2.1
Min	11.6	9.2	0.3
Max	32.6	19.9	6.8
Branch attributes			
Stand Management Cooperative (n_{tree}=52)			
Mean	27.1	18.3	6.0
Std	6.9	3.1	3.5
Min	12.2	10.2	0.2
Max	42.7	23.9	12.6
Vegetation Management Research Cooperative (n_{tree}=30)			
Mean	14.8	10.6	0.9
Std	2.9	1.6	0.6
Min	9.8	7.5	0.1
Max	21.2	14.7	2.3
Swiss needle cast (n_{tree}=122)			
Mean	30.4	23.9	10.0
Std	10.2	7.9	5.8
Min	12.5	11.9	0.5
Max	66.6	45.8	28.3
Precommercial thinning (n_{tree}=19)			
Mean	23.3	14.8	2.1
Std	6.3	3.2	2.1
Min	11.6	9.2	0.3
Max	32.6	19.9	6.8

TABLE 4–Branch attributes of trees sampled from plots under varying silvicultural regimes.

Study	Maximum branch size (mm)			Total number of live branches in a node		
	Min.	Mean	Max.	Min.	Mean	Max
SMC Type 1	4.1	32.8	70.1	1.0	13.8	39.0
SMC Type 2	9.7	26.5	45.5	1.0	15.2	37.0
SNC GIS	3.2	24.4	59.2	1.0	13.7	45.0
SNC CTS	2.6	31.3	91.6	1.0	9.3	48.0
PCT	9.0	30.2	48.3	1.0	13.2	31.0
VMRC	2.9	24.5	42.2	1.0	15.8	41.0

SMC Stand Management Cooperative
SNC GIS Swiss needle cast growth impact study
SNC CTS Swiss needle cast commercial thinning study
PCT Precommercial thinning
VMRC Vegetation Management Research Cooperative

Bole and Crown Size

In the Stand Management Cooperative dataset, mean diameter was significantly greater ($p<0.0001$) and height to crown base significantly lower ($p=0.0421$) on trees from thinned plots. In the Vegetation Management Research Cooperative dataset, mean diameter and total height were significantly greater ($p=0.0143$ and 0.0151, respectively) on the sample trees in the treatment with 9.29 m^2 of total vegetation control per tree. In the precommercial thinning dataset, height to crown base was significantly lower ($p=0.05$) on the trees from thinned plots, but average diameter and total height had not yet diverged in response to thinning. Average diameter ($p=0.0074$) and total height ($p=0.0260$) declined with increasing severity of Swiss needle cast, while height to crown base increased ($p=0.0020$).

Stem Form and Tree Volume

Stem form was significantly affected by treatment in the Stand Management Cooperative, Swiss needle cast, and Vegetation Management Research Cooperative plots. On Stand Management Cooperative plots, thinning significantly ($p<0.0001$) changed stem form from a paraboloid to a more conical shape for a given diameter and total height (Fig. 1); however, neither fertiliser nor pruning had a significant effect. On Swiss needle cast plots, more severe needle cast (decreased plot mean foliage retention) led to more conical stem form ($p<0.0001$). On Vegetation Management Research Cooperative plots, the complete removal of the herbaceous ($p<0.0001$) and woody ($p<0.0001$) vegetation significantly moved stem profiles to a more paraboloid shape for a given diameter and total height. The relative effect of these treatments, however, differed according to time since application.

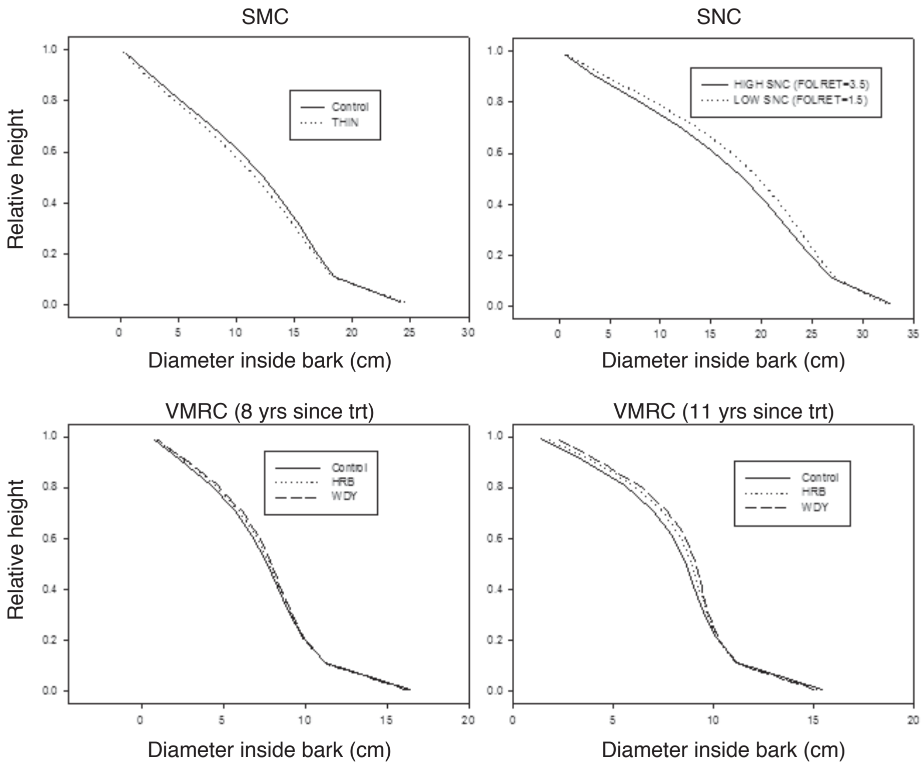

FIG. 1–Predicted diameter inside bark (cm) for trees on Stand Management Cooperative, Swiss needle cast, and Vegetation Management Research Cooperative plots. Diameter at breast height, total height, and height to base of crown are held constant within each study. The treatments effects observed in the Vegetation Management Research Cooperative dataset differed between sites (hence, by time since treatment).

Thinned trees had, on average, 4.8% less volume than unthinned trees of similar diameter and total height. In the Swiss needle cast dataset, the increased taper on severely diseased trees reduced total tree volume by 8.6% for a given diameter, total height, and crown length. Eighteen years after treatment, total tree volume was 1.7% and 3.6% greater under complete removal of the herbaceous and woody vegetation, respectively, when trees of similar diameter and total height were compared. These differences were less than 1.5% 11 years after the treatment.

Branch Characteristics (Number, Angle, and Size)

No treatment effects were found for the number of branches within a whorl or for branch angle, but all silvicultural treatments did significantly affect maximum branch size (Fig. 2). On Stand Management Cooperative plots, fertiliser increased

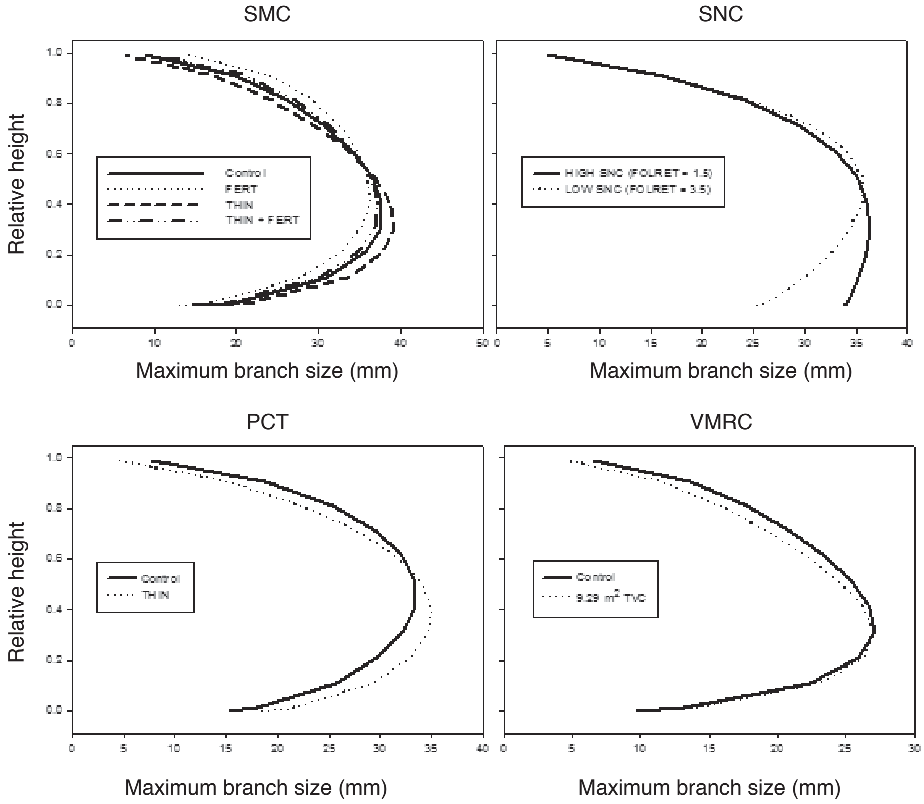

FIG. 2–Maximum branch diameter profiles for the mean tree in each individual dataset. Time since treatment on the Stand Management Cooperative plots was assumed to be 3 years for both fertiliser and thinning.

(p=0.0662) maximum branch size in the upper third of the stem, and thinning significantly increased (p=0.0164) maximum branch size in the lower third of the stem. As a result, the mean maximum branch size profile for combined fertiliser and thinning was quite similar to that of trees on control plots. Treatment effects, however, significantly diminished with time since treatment. On the Stand Management Cooperative Type 3 installation, initial spacing had a significant effect after branch location and tree size were accounted for. Although there was no significant difference between the 762 and 3048 trees/ha plantings at age 12, the mean difference in maximum branch size between the 247 and 2800 trees/ha planting was 20.2%. Precommercial thinning significantly increased (p=0.0022) maximum branch sizes in the lower 50% portion of the stem. For a given bole and crown size, there was very little difference, however, between the treatments. In the Vegetation Management Research Cooperative dataset, the 9.29 m^2 total vegetation control treatment showed moderate evidence (p=0.0606) of significantly reducing maximum branch sizes in the upper third of the crown when compared to the control. Increasing Swiss needle cast severity (lower foliage retention) increased maximum branch sizes in the lower third of the stem and caused a more uniform profile (p<0.0001) (Fig. 2).

AUTOSAW Simulations

Total lumber yield and cubic lumber factor showed relatively little variation, while weighted grade average and total log value had a significantly higher degree of variation (Fig. 3). Consequently, thinning increased mean total lumber yield by 10.3% for a given large-end diameter (p=0.0208) and thinning (p=0.0266), fertiliser (p=0.05), and their interaction increased cubic lumber recovery by 7.0, 3.7, and 1.8%, respectively. Regardless of treatment, over 75% of the lumber was assigned to the No.2 and better grade by AUTOSAW. Estimates of cubic lumber factor and weighted grade average from AUTOSAW differed markedly from those based on Fahey *et al*. (1991) (Fig. 4). AUTOSAW lumber recovery factor and estimated proportions of lumber in three grade classes were a function of large- and/or small-end diameter of the log:

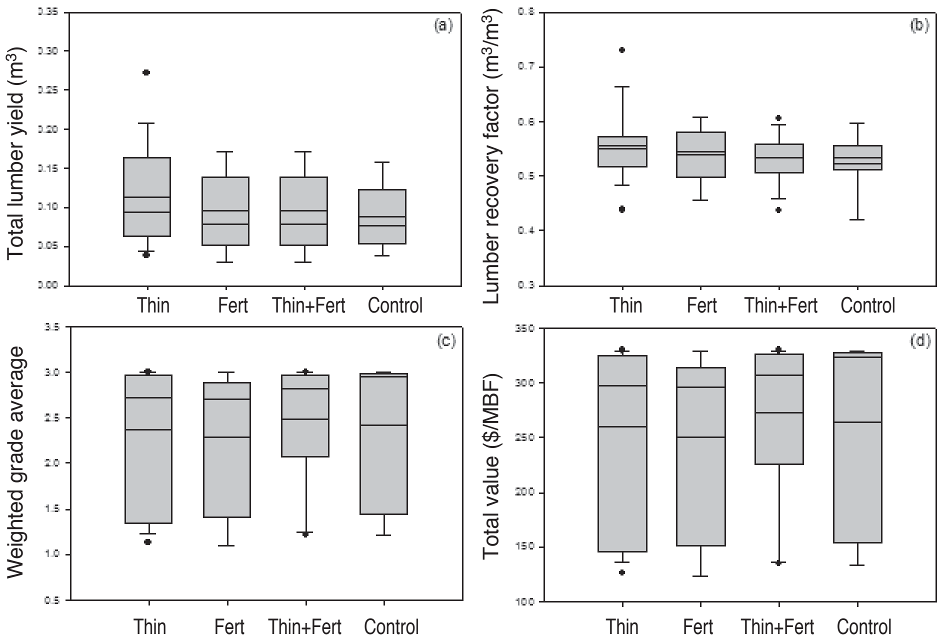

FIG. 3–Simulated lumber recovery by silvicultural treatment: (a) total lumber yield (m^3); (b) lumber recovery factor (m^3/m^3); (c) weighted grade average (Todoroki *et al*. 2005); and (d) estimated plot total log value ($/MBF) from mean 2004 lumber prices.

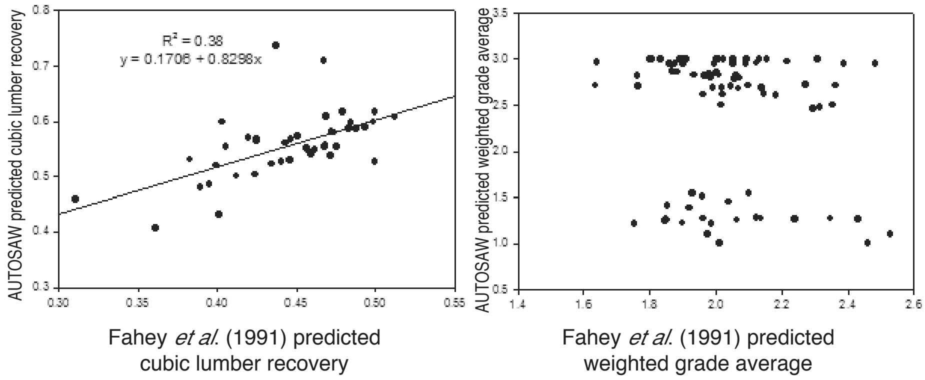

FIG. 4–Lumber recovery factor (left) and weighted grade average (right) predicted from AUTOSAW and Fahey *et al.* (1991).

$$\ln(\text{CLR}) = -1.3961 + 0.0462{*}\text{SED} + 0.0115{*}\text{LED} - 0.0007{*}\frac{\text{SED}}{\text{LED}} \quad [1]$$

$R^2 = 0.44$, RMSE = 0.02

$$\%\text{No1+} = \exp(-1.3699 + 0.0456{*}\text{LED}) \quad [2]$$

$$\%\text{No2} = \exp(-1.8119 - 0.0115{*}\text{SED}) \quad R^2 = 0.22, \text{RMSE} = 0.29$$

$$\%\text{No3} = 1 - \%\text{No1+} - \%\text{No2}$$

where CLR = cubic lumber recovery
SED = small-end diameter (cm)
LED = large-end diameter (cm)
%No1+ is the percentage of lumber volume in No. 1 grade and better
%No2 is the percentage of lumber volume in No. 2 grade
%No3 is the percentage of lumber in the No. 3 and economy grade.

Indices of branch size or number did not contribute significantly to the predictive power of these models.

DISCUSSION

Thinning has consistently been shown to lead to a more cylindrical bole below the live crown and greater upper stem taper within the crown (e.g., Baldwin *et al.* 2000); however, the absolute magnitude of changes is highly dependent on the level of thinning (Karlsson 2000; Lennette 1999). In our analysis of ongoing Douglas fir field trials, both stem form and branch characteristics responded significantly to various silvicultural treatments and Swiss needle cast severity. Thinning and competing vegetation control were two of the treatments that imposed significant changes on stem form, but no corresponding changes could be attributed to the fertiliser treatments investigated in this analysis. The more cylindrical or paraboloid stem form of Douglas fir where competing vegetation was controlled appeared to run counter to the increase in stem taper observed in *Pinus radiata* D. Don

(Snowdon *et al.* 1981). However, because vegetation control significantly accelerates early tree growth, a tree of the same diameter at breast height and total height is probably a dominant in control plots but of lower crown class in the treated plots. Within a stand, trees of lower crown class typically have shorter crowns and a more cylindrical stem form. Fertiliser was previously found to have little or no effect on stem form in *Pinus taeda* L. (loblolly pine) (Jack *et al.* 1988), consistent with Douglas fir in fertiliser-treated Stand Management Cooperative plots.

To our knowledge, the effects of severe defoliation on stem form have not been previously reported. Growth impact analyses typically concentrate on mortality and the large reductions in diameter and height growth that follow defoliation by insects or disease. Stem form changes in this context probably are a relatively minor aspect of growth impact, but may be important when assessing impacts of defoliation.

The literature on branch response to silvicultural treatments is equivocal. Both thinning and fertiliser have been shown to increase the number of branches on Douglas fir (Brix 1981) and Norway spruce (Mäkinen *et al.* 2001). However, the number of branches did not respond to silvicultural manipulation in *P. radiata* (Woollons *et al.* 2002) and in another study on Douglas fir (Grotta *et al.* 2004). Inconsistency in accounting for indirect effects on tree size may account for some of the apparent discrepancy. The effect of fertiliser on maximum branch size was limited to the upper crown, while thinning influenced branches in the lower crown. This pattern supports a previous conclusion that fertiliser tends to have most of its effect in the top half of the crown whereas thinning affects primarily the bottom half (Brix 1981). Not surprisingly, therefore, the response of maximum branch size to thinning cancelled out the response to fertiliser. Two stand factors that can significantly modify maximum branch sizes on a stem and have not been previously reported on are defoliation from a needle cast disease and various levels of vegetation management. The effects of Swiss needle cast were related to the disease biology, while the results of the vegetation management were a bit surprising and require further investigation. However, the effects of vegetation management agree with the finding of Campbell (1963) who indicated that Douglas fir growing faster in height tend to have smaller diameter branches after stem volume is accounted for. Similarly to this study, fertiliser (Brix 1981; Mäkinen *et al.* 2001) and thinning (Medhurst & Beadle 2001) have had little influence on branch angle.

Despite significant differences in stem form and branch size associated with thinning and fertiliser, these responses were not large enough to significantly affect simulated lumber quantity or quality. Moreover, branch characteristics were poor predictors of log weighted grade average, a result similar to recent findings of Todoroki *et al.* (2005). Apparently the knots do not reach a size large enough to influence visual lumber grades (>6.4 cm). Other factors such as juvenile wood content and micro-anatomical properties (density, microfibril angle, grain angle) may be more important for determining lumber yield and quality of young Douglas fir trees. Differences in branch diameter among the treatments represented are still not very large, despite statistical significance. However, as the treated plots mature, branches on trees grown at very wide spacings will become proportionately much larger and most likely will have a drastic influence on quality of lumber recoverable. Likewise, stem form will continue to differentiate and become more and more unfavourable at very wide spacing than at narrow spacings.

The simulation results produced by AUTOSAW and those obtained from the models of Fahey *et al.* (1991) differed considerably. Todoroki *et al.* (2005) made observations on AUTOSAW predictions compared to actual lumber recovery from mill studies. The primary driver of the differences may be the drying of the lumber, which is not accounted for in AUTOSAW. In contrast, the lumber grade prediction models of Fahey *et al.* (1991) were developed on products that were kiln-dried, a process that can introduce numerous additional defects undetectable solely from grain and knot size. In addition, because trees were sampled in the study of Fahey *et al.* (1991) on the basis of diameter, height, and crown length rather than on the basis of known silvicultural regimes, some question remains about applicability to closely regulated plantation regimes. Comparison of AUTOSAW predictions to those from the Fahey *et al.* (1991) equations cannot therefore be construed as a definitive validation of either. Regardless, as rotation ages in Douglas fir become shorter, it may become increasingly important that future product recovery equations and sawing simulators have the capacity to predict modulus of elasticity from models of spatial variation in wood density, with branch size of only secondary importance.

CONCLUSION

Although significant effects of silvicultural treatment on stem form and branch characteristics were observed, their marginal effects were small because they were largely accounted for by the response of diameter at breast height, total height, and crown length (total height minus height to base of crown) and their subsequent use as predictor variables. Consistency in these allometric relationships has facilitated prediction of stem form and branch attributes across a wide range of stand conditions in several other commercially important species (Mäkinen & Colin 1998; Grace *et al.* 1999; Mäkinen *et al.* 2004). A simulation software package is available to reconstruct Douglas fir crown structure and stem form given a tree list (diameter, total height, height to base of crown), total age of the stand, and an estimate of site index (http://www.holoros.com/bcacs.htm). The software can be used to estimate crown profile, predict leaf area by age class, and project knot size and frequency. However, this study suggests that factors such as juvenile wood content and wood density should be incorporated into models if the goal is to simulate the effect of silvicultural treatments on log and product quality, particularly in relatively young Douglas fir. Future studies should concentrate on the effects of intensive silvicultural practices on three-dimensional gradients in wood density and micro-anatomical features.

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